

In Search of Pedagogical Content Knowledge in Science: Developing Ways of Articulating and Documenting Professional Practice

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Received 27 February 2003; Accepted 17 July 2003

Abstract: This study examines the development of ways of documenting and portraying science teachers' pedagogical content knowledge (PCK). As a result of a longitudinal study into science teachers' pedagogical content knowledge, a method is developed for capturing and portraying PCK that comprises two important elements. The first is linked to the particular science content, termed Content Representation (CoRe), and the second is linked to teaching practice, termed Professional and Pedagogical experience Repertoire (PaP-eR). Through this approach new understandings of PCK emerge that are of interest in terms of both academic (knowledge building about PCK) and teaching perspectives. This study includes a full CoRe and one PaP-eR and fully demonstrates how these two elements interact to begin to portray science teachers' pedagogical content knowledge. © 2004 Wiley Periodicals, Inc. *J Res Sci Teach* 41: 370–391, 2004

In his search for the expert pedagogue, Berliner (1988) made clear that teaching for understanding was based on a genuine scholarship of practice. This was displayed through a teacher's grasp of, and response to, the relationships between knowledge of content, teaching, and learning in ways that attest to notions of practice as being complex and interwoven. One consequence of this work was the recognition that teachers' professional knowledge is difficult to categorize and therefore exceptionally difficult to articulate and document.

Berliner was one of a number of researchers at that time who encouraged the education community to pay more attention to teachers' knowledge and to better value professional practice. Definitions of knowledge, and distinctions between these definitions (Cochran-Smith & Lytle, 1999; Connelly & Clandinin, 2000; Fenstermacher & Richardson, 1993; Korthagen & Lagerwerf,

Contract grant sponsor: Australian Research Council.

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DOI 10.1002/tea.20007

Published online in Wiley InterScience (www.interscience.wiley.com).

1996; Richardson, 1994), have impacted on what researchers have looked for, and valued, in attempts to describe a knowledge base that influences teachers' approaches to, and practices of, teaching. However, attempts to articulate links between practice and knowledge have proved to be exceptionally difficult, because, for many teachers, their practice and the knowledge/ideas/theories that tend to influence that practice are often tacit (Schön, 1983).

For school teachers, there is little expectation or obvious reason for such articulation (Loughran, Milroy, Berry, Gunstone, & Mulhall, 2001b) as the demands of time, curricula, and student achievement tend to create a focus more on doing teaching rather than explicating the associated pedagogical reasoning. Importantly, however, if science teaching is to be better understood and valued, such articulation is needed. This study reports on a longitudinal research project with the specific purpose of attempting to capture, document, and portray science teachers' expert knowledge of teaching through the theoretical lens of pedagogical content knowledge (PCK).

During this study, it became increasingly obvious to us that the "traditional ways" of studying PCK were inadequate in terms of our goal of capturing and portraying PCK so that it could be concretely represented to others. Hence, over time, we came to develop what we have termed CoRe and PaP-eR in response to the difficulties with which we were confronted. Through the research and development of CoRe and PaP-eR we came to see that they were both a method for capturing PCK and an approach to portraying this knowledge to others. This investigation outlines the development and use of this method in the hope that it is a useful addition to the body of literature on PCK.

Pedagogical Content Knowledge

Shulman (1986, 1987) proposed that teachers' professional knowledge is comprised of a variety of categories, with one of these categories being PCK. Shulman conceptualized PCK as including "the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that makes it comprehensible for others" (1986, p. 9). It was "the category [of teacher knowledge] most likely to distinguish the understanding of the content specialist from that of the pedagogue" (1987, p. 8). Shulman claimed that teachers needed strong PCK to be the best possible teachers. He asserted that teachers had a unique way of looking at practice and his intrigue with the manner in which they did so encouraged an examination of teachers' pedagogical thinking in ways that, it was anticipated, would reveal what teachers must know to best teach their content to students.

Shulman's notion of PCK created many and varied responses and has been interpreted in different ways (see, e.g., Bromme, 1995; Geddis, Onslow, Beynon, & Oesch, 1993; Gess-Newsome & Lederman, 1999; Grimmett & MacKinnon, 1992; Grossman, 1990). However, regardless of interpretation, PCK has become an accepted academic construct. A common view of PCK is that it is bound up—and recognizable—in a teacher's approach to teaching particular content. The foundation of (science) PCK is thought to be the amalgam of a teacher's pedagogy and understanding of (science) content such that it influences their teaching in ways that will best engender students' (science) learning for understanding.

Shulman's (1986, 1987) approach to thinking about teachers' knowledge led to a shift in understanding and a new valuing of teachers' work such that research began to focus on understanding teaching from the teacher's perspective rather than the previous approach that focused on evaluation and labeling of teachers and teaching behaviors (Feiman-Nemser & Floden, 1986). From this new perspective, researchers began to find ways of examining what

teachers knew (Clandinin & Connelly, 1995; Cochran-Smith & Lytle, 1990). Yet, although PCK as a construct was seductive to researchers, few concrete examples of PCK emerged in subject areas.

As Van Driel, Verloop, and De Vos (1998) noted, although the research community embraced the notion of PCK, the stark reality is that there are few science topic-specific examples in the literature to illuminate this important aspect of teachers' professional knowledge. This is perhaps not so surprising, because, as Carter (1993) suggested, teachers' knowledge is elusive, and there is no language or structure to adequately discuss such knowledge. Related to this is the problem that teachers are often unaware of the knowledge they possess, as it is often contextualized and associated with particular students, events, and classrooms (Kagan, 1990).

Furthermore, the boundaries of PCK are blurry (Loughran, Gunstone, Berry, Milroy, & Mulhall, 2000), thus reinforcing a constant theme in the literature that what exactly PCK comprises is not always clear and consistent. In fact, Barnett (1999) proposed a conceptualization of PCxK (pedagogical *context* knowledge) to specifically link ideas about PCK with the particular teaching context; that is, that PCK is context dependent. Lederman and Gess-Newsome (1992) also highlighted the complexity of the idea of PCK by drawing an analogy between Shulman's conception of teachers' knowledge (comprising mainly subject matter knowledge, pedagogical knowledge, and PCK) and the ideal gas law. Just as the ideal gas law does not perfectly describe the behavior of real gases, Shulman's model of teachers' knowledge also does not perfectly describe classroom teaching. However, it does offer useful insight into improving science teaching (and this is an important link to the CoRe and PaP-eR approach, which is explained later in this study).

Conceptualizing PCK and investigating it in practice has thus developed through a variety of approaches. Often this research has involved exploring what teachers do and do not know about some aspect of teaching a particular topic, and might often include comparisons of teacher knowledge between different teachers (e.g., Magnusson & Krajcik, 1993), between novice and expert teachers (e.g., Clermont, Borko, & Krajcik, 1994), or as a result of some kind of intervention (such as a workshop or preservice course; e.g., Smith & Neale (1989); Van Driel et al. (1998); Veal, Tippins, & Bell (1999)). The relationship between teachers' subject matter knowledge and PCK about a particular topic has also been explored (e.g., Ebert, 1993; Geddis, Onslow, Beynon, & Oesch, 1993; Parker & Heywood, 2000). Thus, much of this research has been concerned with trying to understand various facets of PCK rather than exploring the whole of a teacher's PCK about a particular topic. This is because, as Veal and MaKinster (2001) noted, the development of a teacher's PCK is multifaceted and not linear; therefore, it is a complex task to capture and portray PCK despite the fact that PCK itself is an almost unquestioned academic construct. Not surprisingly, because of its complexity, Van Driel and De Jong (2001) called for a multimethod approach for investigating PCK, which is what we have done in the present investigation. So, what is it that makes PCK so difficult to capture and portray?

Difficulties in Capturing PCK

Although PCK may exist, it is a very difficult process both to recognize and articulate (Loughran et al., 2000), for which there are numerous reasons.¹ A teacher's PCK may not

¹These data sources initially led to the notion of PaP-eRs; however, over time, PaP-eRs were also explicitly suggested by teachers involved in the small group exercises as they illustrated ways of teaching particular aspects of a CoRe. PaP-eRs were developed and refined in concert with the CoRe as teachers' PaP-eRs were continually validated with the original teacher and across other teachers for naturalistic generalizability (Stake & Trumbull, 1982).

be evident to a researcher within the confines of one lesson or teaching experience; an extended period of time (e.g., a unit of work) may be needed for it to unfold (as we came to see over time in this study). Furthermore, as Baxter and Lederman (1999) noted, observations can provide only limited insight into a teacher's PCK, because it is partly an internal construct—thus we must ask teachers to articulate their PCK. PCK is a complex notion, however, and science teachers do not use a language that includes (nor necessarily resembles) the construct of PCK, and much of their knowledge of practice is tacit (Korthagen & Kessels, 1999). In addition, for science teachers there is little opportunity, time, expectation, or obvious reason to engage in discussions helping them to develop tacit knowledge of their professional experience into explicit, articulable forms to share across the profession (Hollon, Roth, & Anderson, 1991).

Because the need to make the tacit nature of practice explicit is not a normal expectation of being a teacher, there is a lack of a common vocabulary among teachers about teaching and learning (Kagan, 1990). Instead, teachers commonly share activities, teaching procedures, and clever insights into teaching and learning that have implicit purposes in practice, but rarely articulate the reasons behind them. Through this research project, our experience has been that asking teachers to talk about their topic-specific PCK (i.e., about why they teach particular content in a particular way) often leads to descriptions of practice that are driven by pedagogical reasons other than those most closely connected with an understanding of the content (e.g., encouraging more active learning). Hence, PCK continues to be a seductive theoretical construct but not an easily identifiable aspect of practice; consequently, there is a lack of readily available concrete examples of PCK in the literature.

Method

The research reported herein offers a new way of uncovering, articulating, and documenting science teachers' PCK that, we believe, creates genuine opportunities for sharing this knowledge within the professional community in ways that are meaningful, useful, and valuable for teachers, teacher educators, and science education researchers. However, coming to develop a method for doing this has been difficult. This is because of the paucity of examples of teachers' PCK about a particular topic that are neat, concrete packages, able to be analyzed and dissected or used as a blueprint for practice by others—as alluded to earlier. The problem then (which is at the heart of the research reported herein) is how to identify and capture PCK and appropriately represent it to others. Therefore, issues of methodology and portrayal were constant throughout our research.

The method we developed to uncover, document, and portray science teachers' PCK comprises two tools: Content Representation (CoRe) and Pedagogical and Professional experience Repertoires (PaP-eRs). The way in which these tools have evolved is outlined in what follows.

Initially, our understanding of PCK was such that we envisaged finding expert science teachers who more than likely had well-developed PCK, but were perhaps unable to personally articulate it. Hence, we sought to detect PCK through such things as: content-specific teaching procedures, such as role-plays, laboratory work, demonstrations, etc.; discussions with teachers about their teaching; classroom observation; and other “traditional” approaches to seeing “knowledge through the practice” of experienced science teachers.

The individual science teachers we interviewed (high school science teachers who were teaching general science in Years 7–10 and had a senior science [Years 11 and 12]—the last 2 years of high school in Australia, with specialism in biology, chemistry, or physics) clearly had

a very good working knowledge of their teaching; however, although we had insights into these science teachers' use of teaching procedures, we did not believe we were uncovering PCK in particular. The next step in developing our methodology was to mix interviewing with observations of classroom teaching. Particular classroom episodes that were noted during lesson observations were used by the interviewer(s) to help in a process of stimulated recall, so that the teacher's/students' actions could be used as a way of revisiting the situation and therefore exploring the nature of the teaching and learning. Again, although we developed ways of better understanding what was happening in the classroom and the factors that influenced the teaching and learning we were observing, we believe we were not actually tapping into these science teachers' PCK. However, it was through this initial work with individual science teachers that we came to recognize the value in developing PaP-eRs (explained in detail later) as one tool in our methodology.

We then moved to working with small groups of experienced science teachers (all high school teachers as explained earlier) as we developed an activity designed to get teachers to think about, and share with others, their knowledge about how to teach particular science content. Working in small groups (three or four per group), the task for the teachers was to consider what they perceived as being the main ideas or concepts in teaching a particular content area and how they would go about helping their students to understand these ideas. Having discussed and agreed upon the main ideas for the content under consideration, the teachers then considered these in terms of a number of framing questions/prompts. This activity led to the development of what we later termed Content Representation, or CoRe.

Through this (slow) development of a method for uncovering PCK (we worked with over 50 science teachers over a 2-year period) it became increasingly clear why there was such a paucity of concrete examples of PCK in the literature. It was now obvious to us that it was not useful to view PCK solely as something residing in an individual teacher, because different but complementary aspects of PCK are revealed through exploration with groups of teachers (CoRes) as opposed to individual teachers (PaP-eRs). Therefore, capturing and portraying science teachers' PCK requires working at both an individual and collective level as, in many ways, PCK resides in the body of science teachers as a whole while still carrying important individual diversity and idiosyncratic specialized teaching and learning practices. An overview of the longitudinal nature of the development of these ideas is given in Table 1.

Participants

As noted earlier, all science teachers involved in this study were high school science teachers. In Australia, high school comprises Years 7–12 (students approximately 13–18 years of age). High school science teachers traditionally teach general science to students in Years 7–10, and thus a range of science topics (e.g., genetics, volcanoes, chemical reactions, particle model, acids and bases, etc.) based on the major content areas of biology, chemistry, earth sciences, and physics. Generally, science teachers then teach across a range of content areas in general science as well as within their field of specialty in the final 2 years of high school (Years 11 and 12). In all cases in this research project, the teachers taught both general science and senior science, so they were familiar with both the different year levels and the curriculum diversity in high school science. The content areas in which the teachers were discussing their PCK was directed toward Years 7–10 general science, and the specific topics that teachers worked on in the development of CoRe and PaP-eRs was a decision they made in response to topics they suggested and felt most adept at exploring in detail.

Table 1
Development of method (CoRe and PaP-eRs) over time

Time Frame	Research Approach	Data	Participants
February to July 1999	Individual interviews with science teachers (duration up to 1.5 hours).	Teaching procedures, stories about teaching episodes, detailed discussions about general pedagogy.*	Secondary science teachers (physics, chemistry, biology and general science), $N = 24$.
June 1999 to November 2000	Classroom observation (ongoing visits—in some cases weekly- to volunteer teachers' classrooms).	Critical incidents in classroom teaching and learning. Access to teachers' and students' understanding of particular teaching and learning situations in science.	Secondary science teachers (chemistry, biology and general science), $N = 12$.
December 1999 to June 2001	Small groups of science teachers workshoping the development of content representations using the outline in Figure 1 as a template.	Development of conceptual basis for teaching particular content. Development of a CoRe approach to an understanding of science teachers' views of content knowledge by examining their understanding of specific content.†	Secondary science teachers (chemistry, biology, general science) in small groups of 3 or 4, $N = 10$ groups.

*These data sources initially led to the notion of PaP-eRs; however, over time, PaP-eRs were also explicitly suggested by teachers involved in the small group exercises as they illustrated ways of teaching particular aspects of a CoRe. PaP-eRs were developed and refined in concert with the CoRe as teachers' PaP-eRs were continually validated with the original teacher and across other teacher for naturalistic generalizability (Stake & Trumbull, 1982).

†The development of CoRes occurred through inquiry into specific content and the way teachers conceptualized the high ideas in that content area. CoRes were developed and refined as small groups worked with one another's responses to the table (see Fig. 1) until there was general agreement that a CoRe was a fair representation of one way of conceptualizing that content. More than one CoRe was created for some topics as different approaches were uncovered toward approaching understanding of that particular content.

CoRe and PaP-eRs Approaches to Capturing PCK

CoRe sets out and discusses science teachers' understanding of particular aspects of PCK (e.g., an overview of the main ideas; knowledge of alternative conceptions; insightful ways of testing for understanding; known points of confusion; effective sequencing; and important approaches to the framing of ideas). These are encapsulated in the prompts in Figure 1 (column 1).

It is crucial to emphasize that CoRe is both a research tool for accessing science teachers' understanding of the content as well as a way of representing this knowledge. Therefore, we used CoRe as an interview tool with groups of science teachers (three or four per group) to elicit their understandings of important aspects of the content under consideration, as well as then using the outcomes of these interviews as the representation itself. As the prompts in column 1 (Fig. 1) are explored in detail with science teachers, their understanding of the nature of the content (e.g., the particle model) and factors shaping that knowledge are raised and become an important data source (full CoRe for the "Particle Model" in Appendix 1). However, a CoRe derived from one group of science teachers should not be viewed as static or as the only/best/correct representation of that content. It is a necessary but incomplete generalization resulting from work with a particular group of teachers at a particular time.

The purpose of CoRe is to help codify teachers' knowledge in a common way across the content area being examined and, through this, to identify important features of the content that science teachers recognize and respond to in their teaching of such content. In fact, in some of the content fields we are researching (e.g., chemical reactions, ecosystems, forces,

IMPORTANT SCIENCE IDEAS/CONCEPTS				
	Big Idea 1	Big Idea 2	Etc.	
PaP-eR 1	1. What you intend the students to learn about this idea			
	2. Why it is important for students to know this.			
	3. What else you know about this idea (that you do not intend students to know yet).			
	4. Difficulties/limitations connected with teaching this idea.			
PaP-eR 2	5. Knowledge about students' thinking which influences your teaching of this idea.			
	6. Other factors that influence your teaching of this idea.			
	7. Teaching procedures (and particular reasons for using these to engage with this idea).			
	8. Specific ways of ascertaining students' understanding or confusion around this idea (include likely range of responses).			
PaP-eR 3				
PaP-eR 4				

Figure 1. CoRe (Content Representation) and associated PaP-eRs (Pedagogical and Professional experience Repertoires); lines from the PaP-eRs represent the links to particular aspects of the CoRe.

genetics, circulatory system) a number of CoRes are readily identifiable—and distinctly different—as different science teachers conceptualize the content in different but equally valid ways.

Attached to the CoRe are PaP-eRs, with links to the aspects of this field that the PaP-eRs bring to life by illustrating how such knowledge might inform effective classroom practice. A PaP-eR offers a window into a teaching/learning situation wherein it is the content that shapes the pedagogy. The PaP-eRs are therefore linked to the CoRe to help to connect the practice seen with the understanding of that particular content. These links then illuminate the decisions underpinning the teacher's actions intended to help the learners better understand the content (see Fig. 1 for a schematic representation of the link between CoRe and PaP-eRs—the lines from the PaP-eRs to different rows and columns in the CoRe illustrate the particular ideas/concepts/content being examined).

The PaP-eRs are about teaching that content in that context and help to illustrate aspects of PCK in action. Importantly, one PaP-eR alone is not enough to illustrate the complexity of the knowledge around particular content. Including a collection of PaP-eRs attached to different (but probably overlapping) areas of the CoRe is crucial in highlighting some of the different blends of elements that are jointly indicative of PCK in that field. The overlap, interplay, and relationship between PaP-eRs in a content area are important in viewing the complex nature of PCK without any one PaP-eR being regarded as representing the nature of PCK itself.

Figure 1 is a schematic overview of how the CoRe and PaP-eRs are conceptualized both in terms of methodology and portrayal of PCK. The CoRe is based on explication of the “big ideas” of the particular content through responses to the prompts in column 1, and the PaP-eRs offer windows into some of these explications by representation in different forms (e.g., descriptions of classroom observations, teaching procedures, curriculum issues, students' alternative conceptions, and so on).

PaP-eRs are developed from detailed descriptions offered by individual teachers, and/or as a result of discussions about situations/ideas/issues pertaining to the CoRe, as well as classroom observations. A PaP-eR therefore develops through the interaction of the prompts, questions, issues, and difficulties (column 1, Fig. 1) that influence the particular approach to teaching that content to which the PaP-eR is tied and reflects the richness of the teacher's understanding of science teaching and learning in that field. Here, it is important to note that a PaP-eR does not necessarily apply to a particular teacher but is a construction by researchers using insights gained in discussions and classroom observations (recognition of this issue has also been noted by Van Driel et al., 1998). However, PaP-eRs are validated through a process of drafting and verification between researchers and teachers—just as the CoRe is developed and refined over time with small groups of teachers.

PaP-eRs therefore emerge from teachers' actual practice and hinge on two important issues:

- PaP-eRs are of a particular content area, and are therefore attached to that content.
- One PaP-eR *cannot alone carry PCK*—a diversity of PaP-eRs helps to shed light on the different aspects of PCK.

If a representation of PCK is to help teachers recognize, articulate, and develop their understanding of that content, then clearly it must be based on an understanding of what it is about the content that the teacher knows (and has come to understand) to purposefully shape the

pedagogy and the associated approach to student learning. As a classroom window, a PaP-eR has the advantage of being set in a context in which the learners are interacting with the subject matter.

The construction of a CoRe and associated PaP-eRs offers a way of addressing the problems of capturing and portraying PCK that have continually confounded previous research. As the PaPe-Rs are attached to the CoRe, they do not need to carry the more comprehensive knowledge informing the practice being illustrated that makes such accounts too cumbersome to be engaging or useful to other teachers. We also argue that PaP-eRs should not have a particular format or style. They should be engaging portrayals of the elements of PCK that are being illustrated. PaP-eRs should have a variety of formats (e.g., interview, observer's voice, journals, window into a lesson, students' voice and actions, annotated resources, etc.—see example in the Results section) so that their portrayal allows the reader to identify with the situation and, as a result of the particular framing of the pedagogy, content, and context, to draw meaning from it.

In concert with the PaP-eRs, the CoRe must be conceptualized as a necessary construction to codify and categorize the knowledge and content under consideration so that it is manageable and useful for others. Well-constructed PaP-eRs will thus bring different aspects of this CoRe to life (as suggested in Fig. 1) and shed new light on the complex nature of PCK for both teachers and researchers. This use of CoRe and PaP-eRs then may create opportunities to better understand, and hence value, the specialized knowledge, skills, and expertise of science teachers by making the tacit and elusive explicit for all audiences.

Results

To illustrate some of the salient features of this approach to capturing and portraying PCK, in this section, we examine some aspects of the CoRe and refer to one PaP-eR (see Appendix 2: “Seeing Things Differently”), concerning the particle model. The CoRe is too cumbersome to display in the body of this article, but is presented in Appendix 1 (“CoRe for the Particle Model”) as an example. A CoRe with the associated PaP-eRs forms a booklet that encapsulates the whole process of portrayal of PCK for a given topic (e.g., the Particle Theory booklet comprises 32 pages in which there is a CoRe and eight PaP-eRs [Loughran et al., 2001b]).

CoRe

The big ideas for the content area for Particle Theory (see Appendix 1) highlight a number of concepts as being commonly viewed as important for students to learn in order to understand this topic (across a range of science teachers that worked on this topic in small groups). The big ideas developed were that:

1. Matter is made up of small bits called particles.
2. There is empty space between particles.
3. Particles are moving (their speed is changed by temperature) and that they appear in a certain arrangement.
4. Particles of different substances are different from one another.
5. There are different kinds of particles that, when joined, are different again. There are different “smallest bits.”

6. There is conservation of matter. Particles do not disappear or get created; rather, their arrangements change.
7. The concept of a model is used to explain the things we observe.

Development of the big ideas for a topic is then an important aspect of articulating one's PCK because it offers access to the way in which science teachers frame the topic, and may be regarded as the main ideas that teachers see as valuable in helping to conceptualize the topic as a whole. These big ideas are then built upon through the second row of the CoRe, which asks teachers to consider why it is important for students to know these big ideas. The responses by the science teachers involved in our research illustrate their reasons for conceptualizing this topic in this way. For example, big idea 2 (refer to big ideas 1–7 just given) is considered important for students to learn because it “explains the ability to compress things and helps to explain events such as expansion and dissolving”; big idea 4 is important for helping students to understand “the observable behaviors of different substances”; and big idea 6 is crucial “because in any reaction involving matter, all of that matter must be able to be accounted for.” When science teachers begin to “unpack” their content knowledge in this way it helps them to focus on what matters in a content area and to teach in ways that have a clear purpose and focus in developing a conceptualization of the subject area, both for themselves and their students.

The fourth row of the CoRe sheds further light on these science teachers' understanding of this topic through a consideration of the perceived difficulties/limitations in teaching these particular big ideas. For example, big idea 1 is seen to carry with it the difficulty that “particles are too small to see,” and therefore one aspect of teaching big idea 1 that “matter is made up of small bits” is influenced by how a teacher considers the need for this issue to be “dealt with” rather than simply relying on a “teaching-as-telling” approach. Another interesting difficulty in this CoRe is with big idea 3, whereby “the term *state* implies that things are separate and fixed.” So, for these science teachers, the specific language associated with understanding the Particle Theory carries an inherent ambiguity that needs to be recognized and addressed to minimize the impact of possible misunderstandings that may emerge through the language of the topic.

This difficulty with language is further compounded by what these science teachers considered as “knowledge of students that also influenced the teaching of these big ideas” (row 5 of the CoRe). For example, it was noted that “students use the terms molecule and atom without understanding the concepts. They simply adopt the language.” Therefore, by recognizing that students may act in this way, these science teachers are clearly aware that students' use of language can be misleading and that it may, at first glimpse, offer an incomplete assessment of their understanding of the concepts. Teachers who think and operate in this way then would clearly recognize a need to delve deeper into students' thinking about a concept beyond accepting their initial ability to use language, as it may well mask a lack of deeper understanding.

Another example of these teachers' “knowledge of students that also influences the teaching of these big ideas” (row 5 of the CoRe) is related to the contradiction between the theoretical view that matter is conserved and a student's belief that “new stuff can appear.” A teacher that recognizes and responds to this contradiction may do so in ways that purposefully shape students' thinking by creating situations wherein cognitive dissonance may be used to create a “need to know.” Alternatively, not recognizing this type of contradiction could lead to later difficulties pertaining to conservation of mass, hence recognizing and responding to the situation is an indication of PCK in this topic, but it could likely remain tacit if the methodological tool of the CoRe was not also a useful prompt for thinking about PCK in this manner.

Finally, the development of a CoRe (in this case Particle Theory) has emerged as a process of development (small groups of three or four teachers working together on the topic), refinement (initial responses to CoRe are refined by other small groups of teachers who question and shape the final product), and validation (individual and small groups of teachers examine the CoRe to determine applicability usefulness and value in terms of the way the ideas are organized and expressed). Importantly, the language used in the CoRe is purposefully not “jargonized” as teachers consistently reworked the language so that it was simple, to the point, and easy to understand.

PaP-eRs

As noted earlier, we are attempting to offer the reader insight into the CoRe and PaP-eRs in a manageable way rather than reproducing all of the work within the body of this report. However, consideration of a PaP-eR, we believe, requires accessing one to illustrate how PaP-eRs link to the CoRe as well as offering insight into one form of PaP-eR writing. Appendix 2 presents the PaP-eR, “Seeing Things Differently,” and is an exploration of how a model can help to explain everyday phenomena (big idea 7) while recognizing that it also needs to be revisited continually, because “macro properties are a result of micro arrangements is hard to understand” (Fig. 1, row 4, big idea 3—“Difficulties/limitations connected with teaching this idea”), and that “many students use a continuous model despite former teaching” (Fig. 1, row 5, big idea 1, “Knowledge about students’ thinking that influences teaching of this idea”).

Overview

The PaP-eR (Appendix 2) is constructed as an insight into both the classroom and Rhonda’s thoughts about her teaching as it is occurring so that the big idea “matter is made up of particles” is played out through a glimpse into this teacher’s classroom practice as well as some of her pedagogical reasoning. The particular format and design of the PaP-eR is constructed to help portray the ideas appropriately to the reader and, clearly, different PaP-eRs will adopt different structures to best convey their message. However, all PaP-eRs have the general format of a brief introduction and are based on the notion that the PaP-eR itself is exploring a specific instance or a small number of associated phenomena, rather than an exhaustive list of interrelated and complex connections across all of the content/concepts associated with the main idea. As noted earlier, the CoRe and PaP-eRs are both methodological tools as well as (when complete and combined) portrayals of PCK in a particular content area. Therefore, the combination of a CoRe and the accompanying PaP-eRs, we argue, offers a new way of portraying concrete examples of science teachers’ PCK in ways that are accessible and understandable while still maintaining the complexity of the PCK through a holistic approach.

As a search of the literature shows, concrete examples of PCK are very difficult to find, yet we have found that the research approach explained in this study does create powerful ways of helping teachers to articulate aspects of their PCK and to explain it in ways that are immediately practical and applicable to their classroom teaching. In many ways, the participants of this research project have viewed their involvement in the process (through data collection via the CoRe and PaP-eRs methods just outlined) as professional development, as they have come to be able to discuss and explain hitherto tacit aspects of their own practice.

Conclusions

The approach to identifying and representing PCK (CoRe and PaP-eRs) developed through our project has been in response to the inability of previous research to adequately capture, portray, and codify science teachers' pedagogical content knowledge in ways that are accessible to, and useable by, other teachers. These problems have led some to consider that the subtleties of quality teaching may defy analysis (Roth, 1998), and although, as the literature continues to illustrate, the subtleties of science teachers' PCK is difficult to uncover and analyze, the CoRe and PaP-eRs approach has certainly made progress in this regard for both teachers and researchers.

Crucial to the value and success of the use of CoRe and PaP-eRs is the depth and breadth of data able to be collected. The time and effort associated with developing cohorts of science teachers to work with, to detail their understandings of particular science content (CoRe) and associated pedagogical influences (PaP-eRs) is extensive, but this method offers what we see as a way of collecting science teachers' PCK and portraying it in an articulable and documentable form.

Through our project, we have been developing CoRes and PaP-eRs across a range of science topics (e.g., chemical reactions, ecosystems, forces, genetics, circulatory system). Interestingly, for us as researchers, each new topic brings with it new demands as understanding the complexity of the content and pedagogy under consideration creates different expectations—just as it does for science teachers themselves. In the work we have completed on the topic “Chemical Reactions,” we included two CoRes. We found that, for many science teachers, their response in framing this topic was somewhat bimodal. One framing response was of chemical reactions as identifiable “common” types of reactions and the associated reasons for these categorizations; a second response was through chemical reactions as requiring a specialist language that was helpful in explaining events. For us, this use of two different CoRes was important because it further highlighted the value in a diversity of approaches to understanding the framing of science topics, and that the development of science teachers' PCK is not governed by a “correct” conceptualization. Rather, it is about the complex interplay between the content, teaching, and learning and the way that teachers use this knowledge to illustrate their expertise and skill in practice.

The shift in approach to researching and documenting PCK outlined in this study is as a result of a recognition of the need to respond to the variety of contextual features that impact on science teaching and learning and to incorporate these into data collection. We also recognize that the eventual illustrations of PCK must be based on the view that PCK is not a single entity, nor is it simple and isolatable. We believe that, for this method (CoRe and PaP-eRs) to be successful, important features must be incorporated into portrayals of practice so that they carry meaning and understanding for others in the education community—both researchers and practitioners. These features include:

- classroom reality (the complexity of a real teaching situation, including a diversity of students' responses);
- teacher's thinking (about the content *and* the responses from the students);
- students' thinking (the links they are/not making and why); and
- what it is about the content that shapes the teaching and learning and why.

One of the distinguishing features of the research reported herein is the way science teachers' understanding of the content, their particular views of teaching and learning within a

context, and the subtleties of their practice in response to the learning (and other) demands of their students are used to offer insights into their PCK. Traditionally, accounts of PCK lack the ability to portray the diversity of ways that particular concepts and content are grasped by science teachers and consequently shape the manner of their teaching. Hence, there is an overwhelming need for the features of portrayals examined and the significance of the approach developed to address this difficulty and advance ways of recognizing and responding to “concretizing” PCK.

The method developed herein combines the need to closely link science content to descriptions of pedagogy through a combination of a Content Representation (CoRe) with insights into teachers’ Pedagogy and Professional experience Repertoires (PaP-eRs) in a way that we believe can offer windows into science teachers’ PCK. Thus, the specialist skills, knowledge, and practice of expert science pedagogues can be better understood and therefore more highly valued within the education community.

The value of this approach is perhaps also enmeshed in an understanding of validity. As Guba (1981) highlighted, allowing the reader to decide the extent to which what is read is relevant to their particular contexts is an important feature of naturalistic inquiry. We trust that examination of the development of this method and the overview of one complete CoRe (see Appendix 1) and PaP-eR (see Appendix 2) offers sufficient context for the reader to develop an understanding of the complex nature of the teaching and learning tied to Particle Theory, so that the PCK contained therein might be accessible and useful to others. In so doing, PCK might move from an acceptable academic construct to a useful framework for teachers to develop and share their content-specific wisdom of practice in meaningful ways that can further enhance the development of science teachers’ professional knowledge and practice. This would permit new ways of seeing and valuing the work of expert science teachers.

Implications

In closing, we draw attention to some of the implications of this research that have emerged over time in hope that it can encourage the science education community to further pursue the applicability and usefulness of the CoRe and PaP-eRs model.

Perhaps the most obvious implication of this work is related to possibilities for science teachers’ professional development. We have used the CoRe and PaP-eRs approach with groups of science teachers who have found the process professionally rewarding as they have begun to examine *their* understanding of *their* practice in new ways. This enhanced sense of understanding has occurred as their tacit knowledge of science teaching and learning has become much more explicit through working on the development of a CoRe and the in-depth discussions of teaching procedures and episodes in constructing PaP-eRs.

Thus, for a science faculty in a school, it is possible that new ways of constructing and understanding science curricula by discussing, dissecting, and reconstructing science teaching and learning through working on a CoRe and PaP-eRs might help them to move beyond the traditionally prescribed content and textbook approach so common in high school science. If this were the case, it would seem fair to assert that a reconsideration of the nature of one’s own pedagogical content knowledge would be created, and individual science teachers may then begin to place greater value on their specific skills and ability, thus enhancing their sense of professionalism and self-worth. In these times of “standards” and the push to better understand what it is that “science teachers need to know and be able to do,” this could be a valuable outcome.

Although we have worked almost exclusively with high school science teachers there are clear possibilities for the CoRe and PaP-eRs approach to be useful for elementary teachers. It has been well documented that elementary teachers are commonly perceived as lacking confidence in their science content knowledge (see, e.g., Appleton, 1992; Appleton & Symington, 1996; Harlen, Holroyd, & Byrne, 1995; Skamp, 1991). However, as PaP-eRs offer insights into the teaching of science, it is possible that there could be an attraction, through PaP-eRs, to activities that work—something important to many teachers but particularly so to elementary teachers (Appleton & Kindt, 1999). In so doing, the link between PaP-eRs and CoRe could offer access to understanding content knowledge as well as the issues surrounding the teaching of that content knowledge that might be helpful in informing elementary teachers about ways of considering the nature of science teaching and learning that encourage further inquiry. Hence, being able to conceptualize the problematic nature of science teaching and learning through the CoRe and PaP-eRs approach might prove to be more informative and insightful and become a catalyst for engaging with science teaching in new ways, breaking down the lack of confidence in the content that is often a barrier to engaging with science teaching and learning *per se*.

Finally, we see CoRe and PaP-eRs as having real and immediate possibilities in science teacher preparation programs. Although preservice science teachers lack the experience of teaching and learning so important in shaping one's PCK, it seems to us that they need opportunities to be introduced to such possibilities to break down the traditional view of learning to teach science as a search for the right "recipe." Clearly, CoRe and PaP-eRs highlight the importance of diversity in understanding teaching and learning in science and the value of questioning and probing the very essence of one's own understanding of science. Therefore, such an approach could be helpful in enhancing the need to better link teaching and learning in meaningful ways for students. Furthermore, science teacher educators could use a CoRe and PaP-eRs approach to broaden the possibilities for student-teachers' learning about science teaching as well as introducing their student-teachers to new ways of absorbing and conceptualizing that which comprises a professional knowledge base in teaching. It could also help to address the "tips and tricks" dilemma (see, e.g., Berry, in press) so common in teacher education, such that comprehending the use and value of CoRe and PaP-eRs could highlight the importance of pedagogical reasoning so that the "normal" student-teacher desire to collect a range of teaching procedures might be challenged through questioning the underpinning of those procedures rather than amassing them at a solely technical level.

We trust that these possibilities are an impetus for others to explore the value of CoRe and PaP-eRs so that PCK might come to be better understood within the teaching profession and that it creates new possibilities for linking the academy with the profession in ways that are meaningful and practical for both.

Appendix 1: CoRe for Particle Theory

This table offers some of the range of ideas that might be covered in teaching Year 7–9 science students on the topic of Particle Theory. The list of important science ideas/concepts are not designed to imply that they are the "only" or the "correct" ideas/concepts for this topic. They are, however, those important science ideas/concepts that teachers in this project suggested and discussed as pertaining to Particle Theory.

APPENDIX 1

Important Science Ideas/Concepts						
1. What you intend the <i>students</i> to learn about this idea.	A. That matter is made up of small bits that are called particles.	B. That there is empty space between particles.	C. That particles are moving (their speed is changed by temperature) and that they appear in a certain arrangement. Because it explains what happens in phase changes (e.g., the need to contain gases is evidence the particles are moving).	D. That particles of different substances are different from one another. Because it explains the observable behaviors of different substances.	E. That there are different kinds of particles that, when joined, are different again. There are different "smallest bits." Because it explains why there are a limited number of elements, but many different kinds of compounds. It also accounts for the concept of atoms and molecules. That the bits themselves are different when combined (e.g., ionic and molecular formation).	F. That there is conservation of matter. Particles don't disappear or get created, rather, their arrangements change. Because the use of models links to important ideas about the way we explore and express views about the nature of science (e.g., the particle theory was constructed rather than discovered).
2. Why it is important for students to know this.	Because it helps to explain the behavior of everyday things (e.g., diffusion).	Because it explains the ability to compress things and helps to explain events such as expansion and dissolving.				
3. What else <i>you</i> know about this idea (that you do not intend students to know yet).	Subatomic structure. Chemical reactions. Ions (links to electricity). Generalizations about properties of materials. More complicated models of matter. Links to diffusion and thermal properties of matter. Particles are too small to see.					
4. Difficulties/limitations connected with teaching this idea.	The use of models is not necessary to comprehend science in every day life. Substances "appear" to disappear when dissolved. What holds particles together? Why don't substances automatically become a gas?	There is a big difference between macro (seen) and micro (unseen) levels (e.g., wood seems solid so it is hard to picture empty space between the "wood" particles).	That macro properties are a result of micro arrangements is hard to understand. The term <i>state</i> implies that things are separate and fixed. It is difficult to imagine particles in a solid moving. There are problems with some representations of liquid (e.g., particles are often shown as being much further apart than they are in solids). "Melt" and 'dissolve' are often used interchangeably in everyday life.		Students can come to think that molecules "disassociate" in boiling water (the confusion between atoms and molecules). Bits are rearranged to create a different substance from existing bits (integrity of particles).	

APPENDIX 1 (Continued)

Important Science Ideas/Concepts			
Linking activities. Behavior of everyday things; For example, putting a marshmallow in a gas jar and changing the pressure so the behavior of the marshmallow is affected. It helps to illustrate the point that small bits move or act differently in response to changes in conditions. Th marshmallow is good because it is an example something they are familiar with—it links to their everyday experience. Explaining thinking and defending views.	Observation. Dry ice sublimating—what's happening?	Questions such as, "Explain why popcorn pops"; "Why when popcorn is pierced does it not pop?"; "Why can we smell onions being cooked when we are at a distance from them?"; "Why does a syringe containing NO₂ appear darker when it is compressed?"	Draw a picture to show what happens to water particles when water boils.
8. Specific ways of ascertaining students' understanding or confusion around this idea (include likely range of responses).	Making predictions about new situations. Tracking one's own learning: For example, "I used to think ." Ask questions such as "What is something that has been bothering you from yesterday's lesson?" Questions such as "Explain why popcorn pops"; "Why when popcorn is pierced does it not pop?"; "Why can we smell onions being cooked when we are at a distance from them?"; "Why does a syringe containing NO₂ appear darker when it is compressed?"	Concept map using the terms: solid; liquid; gas; particles; air; nothing.	Questions such as, "Explain why popcorn pops"; "Why when popcorn is pierced does it not pop?"; "Why can we smell onions being cooked when we are at a distance from them?"; "Why does a syringe containing NO₂ appear darker when it is compressed?"

Put on your "magic glasses" (which are glasses that enable you to see the particles in substances)—what do you see? (i.e., discuss what might be seen through the magic glasses) or draw what you see (then compare and discuss these drawings).

Appendix 2: PaP-eR “Seeing Things Differently”

A PaP-eR on the Particle Model

This PaP-eR illustrates how important the teacher’s understanding of the content is in influencing how she approaches her teaching of the Particle Model of Matter. In this PaP-eR, the teaching unfolds over a number of lessons and is based on the view that understanding how a model can help to explain everyday phenomena requires continual revisiting and reinforcement with students. The PaP-eR closes with an illustration of how inherent contradictions in teaching resources need to be recognized and addressed in order to minimize their level of “interference” in learning specific concepts and how important that is in teaching about models.

Rhonda is a chemistry major with a commitment to making science meaningful for her students. She enjoys teaching about “States of Matter” and has developed a number of important “frames” for approaching the content so that her students will better grasp the ideas rather than simply learn how to “parrot” the appropriate “science” responses in a test.

Rhonda’s framing in the interview—the content. At the Year 7 level it really is only a very limited particle theory that I teach—I don’t go into atomic structure in any serious way. I try to introduce the students to the idea that everything around them is not continuous but is made up of small particles that fit together. I don’t try to give any detail about how they fit together but I do talk with them about the particles being roughly spherical objects that are very, very, very, very tiny.

I know that getting students to use a particle model is not going to fully happen: they will revert to a continuous model when they are pushed. But it is important to start moving them some way along the path—to get them to consider that there may be another way of looking at the things around us. The ideas of the particle model also need to be linked to what is happening during phase changes (melting, freezing, etc.) and that link needs to be at the very tiny level rather than at the macroscopic level. So these two ideas influence how I approach the teaching.

It’s important to continually remind yourself that particle theory at Year 7 and 8 needs to be presented in helpful ways. I believe that maturity plays an important part in what students can actually grasp at a certain age. It’s easy, as the teacher, to forget how conceptually difficult and conceptually abstract this topic is. It is an important topic to teach about though, because it’s one of those building blocks of chemistry that you can build on in layers over the years in science classes rather than trying to do it all at once. It’s conceptually meaty so I enjoy teaching it!

So what do I do? Well, I suppose the first issue is helping the students to start thinking differently about what they’re looking at. It’s important to help them realize that, although the things they are looking at appear to be made up of one thing—like a piece of pipe is made up of one piece of metal—you can break it down until it is made up of lots of small things combining together. A simple analogy is a jar of sand. From a distance it looks like one thing, but up close you can see the individual grains of sand.

From this, you can begin to explain the behavior of everyday things in terms of movements of particles. This is a big shift in thinking for students. Again, you can play with this idea by getting something like a marshmallow and putting it in a gas jar and changing the pressure so the behavior of the marshmallow is affected (the behavior is described later). It helps to illustrate the point about small bits moving or acting differently in response to the conditions. The marshmallow is also good because it is an example of something they are familiar with—it links to their everyday

experiences and that really matters. I've built up quite a few of these examples in my teaching over the years; it's good fun, too.

The other idea to try and aim for is the idea of space, nothing, between the particles: it's really hard. One way of helping to address this is by using the demonstration of mixing water and methylated spirits. You add equal volumes of them together, if each liquid is one big block of water or metho, then the volume should be double, but it isn't so—how come? That helps to make the point about the spaces, so that in this case things can fit between the spaces.

So, overall, I suppose really I'm only concentrating on three things:

1. Things are made up of tiny little bits
2. There is space between the tiny little bits
3. You can use the model to explain phase changes, etc.

But I don't mean to make it sound as simple as that because really what I do is respond to what's happening in the class. Last year I went "down the density path" even though I wasn't intending to. But, because it was students' questions that took us there, I let it go on and followed it for longer. The point really is that the use of the particle model is a way of *thinking* and it's something that the students have to be reminded of so that they think about things from that perspective, rather than reverting to their continuous model perspective.

Rhonda's framing in the classroom—"imagine." The unit starts with Rhonda asking the students to imagine that they have been shrunk down so that they are very tiny and then they fall into a droplet of water on the lab bench. They have to imagine what the droplet looks like from the inside, and then they write a short adventure story and draw a picture of what they can see. The students' pictures show a range of responses, a handful contain dots but most of these are explained as being "the dirt and stuff in the water." Through a number of activities and discussions over several lessons Rhonda introduces the class to the content ideas that she outlined in the interview.

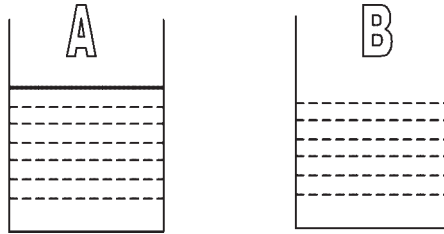
Then Rhonda gets all of the students to make a pair of cardboard glasses. They decorate these in whatever way they wish. She encourages them to use their imagination in designing their "magic glasses." Putting the glasses on is a cue for them to think in terms of particles.

One of the problems I find is that they easily revert back to a continuous model, so putting them in a situation where they wear the glasses and look at something helps them to better understand how the model works to explain what they are seeing. You can get them to put them on at different times throughout the unit and it helps them make the transition to particle model thinking.

In one lesson Rhonda fries onions on the front bench in the laboratory. The students call out from their seats when they start to smell the onions. They track the progress of the smell towards the back of the lab. Rhonda asks them to put on their glasses and look around the room. Can they explain the smell through particle theory? She asks them to think about when they mixed the methylated spirits and water together. With their glasses on they need to describe what is happening as the two liquids combine.

Rhonda shows the class a marshmallow inside a gas jar. By reducing the air pressure in the jar she causes the marshmallow to swell up and then eventually collapse. She asks the students to think about the air inside the marshmallow. If they could 'see' it through their glasses how could they explain what was happening to the marshmallow?

The class revisits their shrinking adventure in the drop of water. Rhonda asks them to think carefully and draw what the inside of a drop of water would be like with the “magic glasses” on. Later in the unit, Rhonda will introduce a new activity based around the way that textbooks represent water as a liquid.



If you look at the pictures in books they often show liquid as particles but the liquid is capped by a continuous line (diagram A), which inadvertently undermines what we’re trying to get students to understand by these representations of a particulate model. The students end up thinking that the water is the clear stuff and the particles are just dots in the water.

Rhonda decides that this year she will ask the class to look at a beaker of water through their glasses and to decide which of the two diagrams best represents water and why they think so.

“If the students are wearing their glasses when they look at a beaker of water they should see diagram B rather than diagram A. And be able to explain why they do!”

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