

## Developing Science Teachers' Pedagogical Content Knowledge

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**Abstract:** This article discusses the concept of pedagogical content knowledge (PCK) within the context of science teaching. First, an attempt is made to define this concept within the tradition of research on teachers' craft knowledge and to identify possible purposes of research on PCK. From this point of view, recent research on science teaching is investigated. This investigation identifies teaching experience as the major source of PCK, whereas adequate subject-matter knowledge appears to be a prerequisite. Finally, an empirical study is presented which focuses on PCK with respect to a specific topic—that is, chemical equilibrium. The effects on teachers' PCK of participation in an in-service workshop and conducting an experimental course in classroom practice are reported. This leads to the identification of elements of PCK teachers can use to promote student understanding. It is concluded that research on topic-related PCK may complement research on student learning of specific topics. © 1998 John Wiley & Sons, Inc. *J Res Sci Teach* 35: 673–695, 1998.

The concept of pedagogical content knowledge (PCK) was introduced by Shulman in a paper in which he argued that research on teaching and teacher education has undeservedly ignored research questions dealing with the content of the lessons taught (Shulman, 1986). The concept of PCK refers to teachers' interpretations and transformations of subject-matter knowledge in the context of facilitating student learning. Notably, PCK encompasses understanding of common learning difficulties and preconceptions of students. As many of the latter have been revealed by research on student learning, submitting PCK to scientific inquiry offers an opportunity to link research on teaching with research on learning.

This article revolves around the question of to what extent PCK has become or may become a valuable concept within the field of research on science teaching. The article consists of three main sections. First, we will concisely review the literature on teachers' craft knowledge and PCK with respect to teaching in general. This section mainly serves to clarify the concept of PCK and to identify possible purposes of research on PCK. The second section discusses the literature on teachers' craft knowledge and PCK within the domain of science education. Finally, in the third section, an example of an empirical study is presented. This study focuses on the

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development of teachers' PCK with respect to a specific topic (i.e., chemical equilibrium) within the context of an in-service program.

## Background

### *Teachers' Craft Knowledge*

In the past decade, attention in research on teaching and teacher education has shifted from observable behaviors or teaching skills to teachers' knowledge and beliefs. This shift was influenced by a growing dissatisfaction with the results of process-product research. Doyle (1990) argued that the focus in process-product research on indicators of effectiveness has led to a fragmented and mechanistic view of teaching in which the complexity of the teaching enterprise is not acknowledged. To understand why teachers behave as they do, it is necessary to investigate how teachers construct meaning in classroom settings (Doyle, 1990). Initially, research on teachers' knowledge and beliefs focused on teachers' thought processes (Clark & Peterson, 1986). More recently, the interest in teachers' practical knowledge (Carter, 1990) or craft knowledge (Grimmett & MacKinnon, 1992) has increased. Although researchers differ in their research purposes and definitions, craft knowledge broadly refers to the knowledge teachers have with respect to their teaching practice. For some, research on craft knowledge implies the acknowledgment of the complex and the context specific nature of teaching, and may therefore contribute to the empowerment of teachers and to an enhancement of the status of teaching as a profession (Doyle, 1990).

The concept of craft knowledge has been the subject of controversy. Tom and Valli (1990) reviewed some major criticisms, such as the supposedly nonscientific nature of craft knowledge and the conservatism inherent in teaching practice. They suggested that the codification of craft knowledge, sensitive as it is to various contexts and contrasting conceptions of good teaching, might turn out to be "a contradiction in terms" (Tom & Valli, 1990, p. 390). Grimmett and MacKinnon (1992) tried to solve this dilemma by defining craft knowledge *not* as "a knowledge base as such, but as a framework for helping prospective and experienced teachers develop their repertoire of responses, understandings, and magical tricks" (p. 441). According to Grimmett and MacKinnon, the essence of craft knowledge pertains to a "teaching sensibility" rather than to "a knowledge of propositions" (p. 393).

In this article, we define craft knowledge as integrated knowledge which represents teachers' accumulated wisdom with respect to their teaching practice. As this knowledge guides the teachers' actions in practice, it encompasses teachers' knowledge and beliefs with respect to various aspects such as pedagogy, students, subject matter, and the curriculum. Although deeply rooted in teachers' practical work, craft knowledge is, in our view, not opposite theoretical or scientific knowledge. Instead, craft knowledge encompasses knowledge derived from prior education as well as from ongoing schooling activities (cf. Beijaard & Verloop, 1996). Moreover, craft knowledge is supposedly influenced by factors related to teachers' personal backgrounds and by the context in which they work (cf. Hoyle & John, 1995). As a consequence of this definition, research on craft knowledge cannot lead to the establishment of a knowledge base with a prescriptive nature. However, research on craft knowledge should attempt to surpass the idiosyncratic level of individual narratives. As for us, we are looking for common patterns in craft knowledge and in the development of this knowledge to develop "frameworks" in the sense of Grimmett and MacKinnon (1992). Moreover, we believe that research on craft knowledge can lead to the formation of a knowledge base which, although different in nature and content, may prove to be a vital addition to existing educational knowledge bases (cf. Verloop, 1992).

### *Pedagogical Content Knowledge*

Shulman introduced PCK as a specific category of knowledge “which goes beyond knowledge of subject matter per se to the dimension of subject matter knowledge *for teaching*” (Shulman, 1986, p. 9). The key elements in Shulman’s conception of PCK are knowledge of representations of subject matter on the one hand and understanding of specific learning difficulties and student conceptions on the other. Obviously, these elements are intertwined and should be used in a flexible manner: The more representations teachers have at their disposal and the better they recognize learning difficulties, the more effectively they can deploy their PCK.

In a later article, Shulman included PCK in what he called “the knowledge base for teaching.” This knowledge base consists of seven categories, three of which are content related (i.e., content knowledge, PCK, and curriculum knowledge). The other four categories refer to general pedagogy, learners and their characteristics, educational contexts, and educational purposes (Shulman, 1987). Whereas Shulman’s knowledge base encompasses every category of knowledge which may be relevant for teaching, our definition of craft knowledge is restricted to types of knowledge which actually guide the teachers’ behavior during classroom practice. Within our own definition of craft knowledge (cf. previous section), we consider PCK to be a specific form of this craft knowledge. This is explained as follows. PCK implies a transformation of subject-matter knowledge, so that it can be used effectively and flexibly in the communication process between teachers and learners during classroom practice. Thus, teachers may derive PCK from their own teaching practice (e.g., analyzing specific learning difficulties) as well as from schooling activities (e.g., an in-service course on student conceptions). More important, when dealing with subject matter, teachers’ actions will be determined to a large extent by their PCK, making PCK an essential component of craft knowledge.

Elaborating on Shulman’s work, other scholars have adopted the two key elements of PCK mentioned above (i.e., knowledge of comprehensible representations of subject matter and understanding of content-related learning difficulties). Moreover, each of them has extended the concept by including in PCK some of the categories of knowledge distinct in Shulman’s knowledge base for teaching. Table 1 summarizes the conceptualizations of PCK of various authors. For example, Grossman (1990) perceived PCK as consisting of knowledge of strategies and representations for teaching particular topics and knowledge of students’ understanding, conceptions, and misconceptions of these topics (i.e., Shulman’s two key elements). In addition, PCK is composed of knowledge and beliefs about the purposes for teaching particular topics and knowledge of curriculum materials available for teaching. In Grossman’s model of teacher knowledge, PCK is at the heart surrounded by three related categories: namely, knowledge of subject matter, general pedagogical knowledge and contextual knowledge. Grossman identified the following sources from which PCK is generated and developed: (a) observation of classes, both as a student and as a student teacher, often leading to tacit and conservative PCK; (b) disciplinary education, which may lead to personal preferences for specific purposes or topics; (c) specific courses during teacher education, of which the impact is normally unknown; and (d) classroom teaching experience.

Marks (1990) also broadened Shulman’s model by including in PCK knowledge of subject matter per se as well as knowledge of media for instruction. In a discussion of sources of PCK, however, Marks perceived the development of PCK as an integrative process revolving around the interpretation of subject-matter knowledge and the specification of general pedagogical knowledge, thereby focusing on Shulman’s two key elements. Marks also discussed some ambiguities in PCK by presenting examples in which it is impossible to distinguish PCK from either subject-matter knowledge or general pedagogical knowledge.

Table 1  
*Knowledge components in different conceptualizations of pedagogical content knowledge*

Scholars	Knowledge of:						
	Subject matter	Representations and Strategies	Student Learning and Conceptions	General Pedagogy	Curriculum and Media	Context	Purposes
Shulman (1987)	<sup>a</sup>	PCK	PCK	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>	<sup>a</sup>
Grossman (1990)	<sup>a</sup>	PCK	PCK	<sup>a</sup>	PCK	<sup>a</sup>	PCK
Marks (1990)	PCK	PCK	PCK	<sup>b</sup>	PCK	<sup>b</sup>	<sup>b</sup>
Cochran, et al. (1993)	PCK <sup>g</sup>	<sup>b</sup>	PCK <sup>g</sup>	PCK <sup>g</sup>	<sup>b</sup>	PCK <sup>g</sup>	<sup>b</sup>
Fernández-Balboa & Stiehl (1995)	PCK	PCK	PCK	<sup>b</sup>	<sup>b</sup>	PCK	PCK

<sup>a</sup>Distinct category in the knowledge base for teaching.

<sup>b</sup>Not discussed explicitly.

Based on an explicit constructivist view of teaching, Cochran, DeRuiter, and King (1993) renamed PCK as pedagogical content *knowing* (PCKg) to acknowledge the dynamic nature of knowledge development. In their model, PCKg is conceptualized much broader than in Shulman's view. PCKg is defined as "a teacher's integrated understanding of four components of pedagogy, subject matter content, student characteristics, and the environmental context of learning" (Cochran et al., 1993, p. 266). Ideally, PCKg is generated as a synthesis from the simultaneous development of these four components.

The idea of integration of knowledge components is also central in the conceptualization of PCK by Fernández-Balboa and Stiehl (1995). These authors identified five knowledge components of PCK: subject matter, the students, instructional strategies, the teaching context, and one's teaching purposes.

The preceding discussion was not meant to be exhaustive. Instead, we have tried to demonstrate that there is no universally accepted conceptualization of PCK. Between scholars, differences occur with respect to the elements they include or integrate in PCK, and to specific labels or descriptions of these elements. Yet, we suggest that all scholars agree on Shulman's two key elements—that is, knowledge of representations of subject matter and understanding of specific learning difficulties and student conceptions. In addition, there appears to be agreement on the nature of PCK. First, as PCK refers to *particular topics*, it is to be discerned from knowledge of pedagogy, of educational purposes, and of learner characteristics in a general sense. Second, because PCK concerns the *teaching* of particular topics, it may turn out to differ considerably from subject-matter knowledge per se. Finally, all scholars suggest that PCK is developed through an integrative process rooted in classroom practice, implying that prospective or beginning teachers usually have little or no PCK at their disposal. This supports our view described above, that PCK is indeed a specific type of teachers' craft knowledge.

*Purposes for Research on PCK.* Concluding the discussion in this section, we propose two main purposes for research on teachers' PCK:

1. As little is yet known about the ways teachers transform subject-matter knowledge, how they relate their transformations to student understanding, and how they develop these abilities, research on these themes is part of a "missing paradigm" (Shulman, 1986, p. 7).
2. To facilitate the development of prospective teachers' PCK and to prevent every teacher from reinventing the wheel, research on PCK may resolve a blind spot in both preservice and in-service teacher education (Verloop, 1992).

### Research on Science Teachers' Craft Knowledge and Pedagogical Content Knowledge

In this section, the focus of attention is shifted toward research in science teaching. Our aim is to determine to what extent research on science teaching has paid attention to science teachers' craft knowledge in the last decade. Rather than presenting an exhaustive review, it is our purpose to identify specific lines of research in the domain of science teaching *from a craft knowledge perspective*. This implies that studies which do not explicitly relate teachers' knowledge and beliefs to classroom practice are either omitted or not commented upon (however, see Anderson & Mitchener, 1994). Analogous to the previous section, we will start with a brief summary of recent research on science teachers' craft knowledge from a generic point of view. This summary revolves around studies on knowledge and beliefs about the nature of science, and about the teaching and learning of science. Next, we will discuss in more detail studies on science teach-

ers' pedagogical content knowledge (cf. Tobin, Tippins, & Gallard, 1994). Included are some studies on science teachers' subject-matter knowledge in relation to teaching practice which do not explicitly refer to PCK. However, these studies are interpreted from a PCK perspective.

### *Science Teachers' Craft Knowledge*

*The Nature of Science.* Research on science teachers' conceptions of the nature of science appears to have a long tradition (Lederman, 1992). In general, these studies amount to the conclusion that irrespective of their academic background, science teachers possess limited knowledge of the history and philosophy of science (King, 1991; Gallagher, 1991) and as a consequence, hold inadequate or naive conceptions of the nature of science (Abd-El-Khalick & BouJaoude, 1997). For example, many teachers appear to hold positivist views, believing that the substantive content of science is fixed and unchangeable rather than tentative. Pomeroy (1993), however, reported relatively many "nontraditional views" of science among science teachers as compared to scientists. She suggested that such views may result from both teachers' "actual practice with children" as well as from "a growing awareness of and commitment to constructivism among educators" (Pomeroy, 1993, p. 272). Yet, the influence of teachers' conceptions of the nature of science on classroom practice is not unambiguously ascertained, owing to "the strong influence of curriculum constraints, administrative policies, and teaching context on the translation of teachers' conceptions into classroom practice" (Lederman, 1992, p. 348).

*The Teaching and Learning of Science.* Many studies on teachers' conceptions of the teaching and learning of science have been conducted in the context of the implementation of a conceptual change approach. As constructivist epistemology is based upon specific assumptions regarding the nature of knowledge and knowledge acquisition, the implementation of a conceptual change approach may have far-reaching consequences for teachers (Prawat, 1992). In this context, teachers' beliefs about teaching and learning appear to have a pervasive influence on classroom practice (Appleton & Asoko, 1996). Studies focus either on the effects of in-service (Constable & Long, 1991; Porlán Ariza & García Gómez, 1992; Hand & Treagust, 1994) or preservice programs (Hewson & Hewson, 1987, 1989; Stofflett, 1994) or on the actual implementation in classroom practice (Johnston, 1991; Briscoe, 1991; Cronin-Jones, 1991; Glasson & Lalik, 1993; Tobin, 1993). Both in-service and preservice training programs are reported to result in changes in the participants' conceptions of teaching and learning science. Specifically, conceptual change strategies are adopted as they are found to be intelligible or attractive. When it comes to the implementation of such strategies in classroom practice, however, problems are reported. Teachers' existing belief structures (Cronin-Jones, 1991) or their commitment to the existing curriculum (Johnston, 1991) or their colleagues (Tobin, 1993) are among the factors that can hinder the implementation. Discrepancies between conceptions teachers express and their actual classroom behavior are observed (Briscoe, 1991; Johnston, 1991). However, some case studies claim distinct, although subtle changes in both teachers' conceptions and their classroom practice toward constructivist ideas. These changes seem to take place on the conditions that sufficient time and professional support are available (Glasson & Lalik, 1993; Tobin, 1993; Appleton & Asoko, 1996). For that matter, these results themselves seem congruent with the basics of constructivist epistemology.

*Relations between the Nature of Science and the Teaching and Learning of Science.* Another group of studies investigated relations between science teachers' conceptions of the nature

of science and their knowledge and beliefs about the teaching and learning of science. Studies in which teachers' conceptions are explicitly connected with their actual teaching practice reveal an apparent distinction between experienced teachers and prospective or beginning teachers. Experienced teachers appear to have developed a conceptual framework in which knowledge and beliefs about science, subject matter, teaching and learning, and students are interrelated in a coherent manner, while their teaching behavior seems consistent with this framework (Brickhouse, 1990). However, individual teachers may have developed quite different frameworks or "functional paradigms", even when they teach the same curriculum (Lantz & Kass, 1987). Tobin and McRobbie (1996) described four "cultural myths" that determine an experienced science teacher's classroom practice. Among others, these myths refer to the transmission of knowledge and the maintenance of the rigor of the curriculum. From an innovative point of view, these myths are perceived as conservative forces.

For beginning and prospective science teachers, a different picture emerges. These teachers often seem to experience conflicts between their personal views of science and science teaching on the one hand and their own actual classroom practice on the other (Brickhouse & Bodner, 1992). Moreover, their personal views sometimes show internal conflicts and their classroom practice may be variable. Powell (1994) identified some constraints in this respect, such as an influential and conservative cooperating teacher, unrealistic expectations about students' motivation, and insufficient laboratory facilities. Roberts and Chastko (1990) studied beginning science teacher thinking in relation to reflective capability. The latter seemed to vary considerably. Moreover, the authors were hardly successful in developing this capability.

*Summary.* Summarizing the above, it appears that within research on science teachers' craft knowledge so far, many studies focus on teachers' conceptions of the teaching and learning of science. In some studies, these conceptions are related to conceptions about the nature of science. The latter studies reveal a significant distinction between experienced teachers and prospective or beginning teachers.

### *Science Teachers' Pedagogical Content Knowledge*

In a number of studies, teaching practice was investigated as a function of familiarity with a specific domain. These studies lead to similar results, indicating that teachers, when teaching unfamiliar topics, have little knowledge of potential student problems and specific preconceptions, and have difficulties selecting appropriate representations of subject matter. Moreover, when teaching unfamiliar topics, teachers express more misconceptions (Hashweh, 1987) and they talk longer and more often, and mainly pose questions of low cognitive level (Carlsen, 1993). In only one of these studies (Sanders, Borko, & Lockard, 1993), these results are interpreted in terms of PCK rather than subject-matter knowledge. It is stated that experienced science teachers, when teaching a topic out of their area of certification, seem to be sustained by their wealth of general pedagogical knowledge, while their PCK is limited. The authors also noticed that experienced teachers quickly learn the new content as well as adequate content-specific instructional strategies, while relying on their knowledge of general pedagogy. The latter helps them to maintain the flow in their classes. The authors concluded that pedagogical knowledge provides a framework for teaching that is "filled in by content knowledge and pedagogical content knowledge . . . when teachers taught within and outside their science area" (Sanders et al., 1993, p. 733).

Smith and Neale (1989) studied the effects of an in-service workshop—that is, a summer program for elementary teachers—that focused upon the implementation of conceptual change

strategies in science teaching. The program offered opportunities to practice these strategies in a science summer camp. The authors conclude that the program was particularly successful in promoting teachers' knowledge of specific contents. Also, beliefs about the nature of science changed toward constructivist views. However, Smith and Neale reported only marginal success with respect to the development of PCK. This is explained by the fact that participants were still constructing a "deeply principled conceptual knowledge of the content" (Smith & Neale, 1989, p. 17), the latter apparently being perceived as a prerequisite for the development of PCK.

Leinhardt and Smith (1985) investigated the subject-matter knowledge of expert teachers in elementary mathematics. They chose a difficult topic—fractions—and investigated teachers' subject-matter knowledge of this topic by means of interviews and card-sorting tasks as well as observations of lessons. The authors reported that although expert teachers may seem quite similar in their knowledge of subject matter per se, their classroom presentations of it may differ substantially. The identification of these differences is considered to be a potential source for "in-service support that is tied to lesson presentation rather than to independent thematic issues" (Leinhardt & Smith, 1985, p. 269). As the results of this study, which predated Shulman's introduction of the concept of PCK, refer to differences in the ways teachers transform and present subject matter in relation to student difficulties, they can be interpreted in terms of differences in PCK.

In two partially overlapping studies, Clermont, Krajcik, and Borko (1993, 1994) investigated chemistry teachers' PCK with respect to chemical demonstrations as an instructional strategy. The second study compared PCK of experienced and novice demonstrators, concluding that experienced teachers possess a greater repertoire of representations and strategies when demonstrating a particular topic. Moreover, they are able to use certain demonstrations more flexibly for various purposes, and they can relate their demonstrations more effectively to student learning than novices. In the first study, the effects on PCK of an in-service workshop for novice demonstrators were investigated. As growth of novices' PCK toward that of experienced demonstrators was observed the authors concluded that PCK "can be enhanced through intensive, short-term, skills-oriented workshops" (Clermont et al., 1993, p. 41).

Adams and Krockover (1997), who studied the development of beginning science teachers' PCK, found that knowledge of instructional strategies was derived both from experiences as a learner and as a teacher or teaching assistant. Knowledge development appeared to be dominated by individual and contextual factors. This resulted, however, among others, in the adoption of conventional instructional strategies, stressing procedures instead of student understanding.

Geddis (1993) studied the transformation of preservice science teachers' subject-matter knowledge into "teachable content knowledge." According to Geddis, PCK plays a critical role in this transformation process. This conclusion was based on a vignette in which a discussion among preservice teachers about students' misconceptions (viz. about electrical current) in comparison to their own views appeared to promote the development of subject-matter representations and instructional strategies.

The transformation of subject-matter knowledge in the context of preservice science teacher education was also studied by Lederman and coworkers. In one of their studies, the subject-matter structures of preservice biology teachers were investigated during a year of professional teacher education (Gess-Newsome & Lederman, 1993). These knowledge structures appeared to be mainly derived from college science coursework. While these structures were often vague and fragmented on entering teacher education, they developed toward more coherent and integrated views of biology during teacher education. Most important, however, was the observation that the translation of these subject-matter structures into classroom practice appeared to be complicated by classroom complexity. The authors suggested that until a teacher has gained ex-

perience and masters basic classroom skills, it may be unrealistic to expect a readily accessible and useful translation of subject-matter knowledge into classroom practice. In another study of knowledge development during teacher education, Lederman, Gess-Newsome, and Latz (1994) investigated the self-reported changes in preservice science teachers' conceptions of subject matter and pedagogy. Although distinct changes in both knowledge domains seem to take place mainly as a result of teaching experiences, preservice teachers appear not to integrate these domains. Again, the authors explained that this results from a lack of teaching experience, suggesting that "with the benefit of experience and continual use of one's subject matter structure for purposes of teaching, the division between pedagogical knowledge and subject matter knowledge may become blurred" (Lederman et al., 1994, p. 143). Thus, the development of PCK may be postponed until teachers reach this stage.

*Summary.* Summarizing the research on science teachers' PCK, it appears that familiarity with a specific topic in combination with teaching experience positively contributes to PCK. Moreover, general pedagogical knowledge may constitute a supporting framework for the development of PCK. Experienced science teachers' PCK may differ considerably, even when their subject-matter knowledge is similar and when they teach the same curriculum. These differences appear from the use of different representations and instructional strategies during classroom practice.

### *Conclusions from the Literature*

We explained in the introduction to this section that we would review the literature on science teaching, looking for studies which contribute to an understanding of science teachers' craft knowledge. Specifically, our interest concerns the application of the concept of pedagogical content knowledge in this domain. We observed numerous studies in which science teachers' knowledge and beliefs are explicitly related to teachers' classroom practice. The impact of constructivist epistemology seems to be important in this respect. As constructivism emphasizes the role of previous experience in knowledge construction processes, it is not surprising that teachers' knowledge is studied in relation to their practice in research from this point of view.

From the literature discussed above, we can draw the following conclusions:

1. It appears that the craft knowledge guiding experienced science teachers' classroom practice is constituted by a framework, integrating knowledge and beliefs about the teaching and learning of science, the nature of science, subject matter, and students. In particular, conceptions about the teaching and learning of science seem to exert a major influence on teaching practice. As these conceptions appear to be rather stable, the innovation of science education may be seriously complicated by science teachers' craft knowledge. Specific programs for teacher education, inspired by constructivist innovations, may result in distinct changes in teachers' conceptions about the teaching and learning of science. There is no clear picture as yet, however, whether these changes are lasting and whether they consistently influence classroom practice.
2. Although the possibility to distinguish PCK from subject-matter knowledge has been the subject of controversy (Marks, 1990; Tobin et al., 1994), studies on science teachers' PCK indicate that a thorough and coherent understanding of subject matter acts as a prerequisite, preceding the development of PCK. This conclusion applies both to studies on the effect of the teaching of unfamiliar topics (e.g., Sanders et al., 1993) and to studies in the context of teacher education (e.g., Smith & Neale, 1989). The other crucial factor in this development is, obviously, teaching experience. This explains why prospective or novice science teachers usually express little to no PCK (e.g., Leder-

man et al., 1994). Teacher training programs usually do not exert a major influence on science teachers' PCK (for example, Smith & Neale, 1989), although Clermont et al. (1993) claimed a significant improvement as a result of a specific workshop.

These conclusions correspond with the findings of Grossman (1990), cited earlier. Grossman identified four sources of PCK, attributing a positive influence to both classroom teaching experience and disciplinary education (i.e., knowledge of subject matter). Either a negative or conservative influence (i.e., observation of classes) or an unknown impact (i.e., specific courses for teacher education) is attributed to the other two sources.

3. Another conclusion from the studies on science teachers' PCK is that most scholars focus on the nature and the development of PCK in relation to other types of knowledge. For example, Sanders et al. (1993) stressed the supporting function of general pedagogical knowledge, whereas others (Clermont et al., 1993, 1994; Adams & Krockover, 1997) applied the concept of PCK to an instructional strategy (e.g., chemical demonstrations), thus interpreting PCK as a specification of pedagogical knowledge rather than a blend of subject-matter knowledge of specific topics and general pedagogical knowledge. Lederman and Gess-Newsome (1992), reacting to Shulman's work cited above (Shulman, 1986, 1987), even questioned the relevance of the concept of PCK altogether. Although the authors acknowledged the importance of "the interaction between subject matter knowledge and pedagogical knowledge as a function of experience" (p. 19), they considered the question of whether pedagogical content knowledge is an important separate domain of knowledge "more of a theoretical argument than a practical one" (p. 19).

As a consequence of this emphasis on general aspects of PCK, the explicit attention for science teachers' knowledge and beliefs with respect to the teaching of specific topics is still marginal. This observation is remarkable given the fact that more than 10 years have passed since Shulman urged researchers of teacher thinking and teacher knowledge to put the content of education high on their agendas, and introduced the concept of PCK particularly for this purpose. The absence of studies on specific topics implies that we cannot yet formulate conclusions with respect to the purposes for research on science teachers' PCK mentioned earlier: At the level of specific topics, research does not inform us about the way science teachers transform subject-matter knowledge and how they relate their transformations to student understanding. Neither have we found specific input for teacher education in this respect. It is important to note that this conclusion applies to *research* on teachers' PCK. Journals focusing on the teaching of specific subjects often contain articles in which a teacher explains his or her successful ways of dealing with specific topics (e.g., *Journal of Chemical Education*). Although these articles are valuable, as the authors have succeeded in making their PCK explicit, we do not consider such articles to be research reports.

As an example of a study which aims at contributing to the purposes mentioned above, we will next present an empirical study on teachers' PCK of a specific topic, that is, chemical equilibrium. This study was conducted in the context of an educational innovation aimed at promoting conceptual change among students when they were introduced to the concept of chemical equilibrium.

## Empirical Study

### *Context*

The present study was conducted within a long-term research project in The Netherlands on chemical education, in which the concept of chemical reaction was central (De Vos & Ver-

donk, 1985). The concept of chemical equilibrium was chosen because the introduction of this concept challenges the conceptions about chemical reactions students have derived from previous education. Therefore, the introduction of chemical equilibrium offers an opportunity to study processes of conceptual change with respect to chemical reaction among students. A specific research purpose concerned the identification of factors either promoting or hindering such processes. Research results focusing on student learning are described by Van Driel, De Vos, & Verloop (in press).

To achieve this purpose, both (a) an experimental course on chemical equilibrium for students of upper-secondary education, and (b) an in-service workshop for chemistry teachers using the experimental course in their own classes were designed. We applied a qualitative research design (see below) in which three cycles of designing, implementing, evaluating, and reflecting on the experimental course were conducted. In the course of the second and third cycles, two consecutive versions of the in-service workshop were designed, implemented, and evaluated. In what follows, we will focus on the third cycle. After elaborating on the design of the workshop and the experimental course, we will present information about the participants and about the way the study was designed. Next, effects of the workshop and the experimental course on participants' PCK of chemical equilibrium will be described. Finally, we will discuss these results.

### *Design of Workshop and Experimental Course*

The workshop's overall purpose was to enhance chemistry teachers' PCK of chemical equilibrium. Specifically, the aims were to improve chemistry teachers' abilities to recognize specific preconceptions and conceptual difficulties related to chemical equilibrium, and to promote their use of interventions and strategies promoting conceptual change during classroom practice. These goals were to be realized by a combination of teachers' use of our experimental course in their own classes and their participation in the workshop. Therefore, workshop meetings were organized before, during, and after the period in which the experimental course was used.

As most of the workshop's participants were chemistry teachers who had been teaching chemical equilibrium for several years, we expected all of them already to possess PCK about this topic to some degree. On the other hand, we assumed that these teachers could benefit from the results of research on student learning of chemical equilibrium and of our educational analyses of chemical literature and curriculum materials dealing with chemical equilibrium. Combining these assumptions, we designed the workshop meetings as follows:

1. The first meeting focused on the PCK of chemical equilibrium participants held on entering the workshop. Therefore, participants performed and discussed chemical experiments and assignments from current chemistry textbooks. Moreover, they were asked to react to authentic student responses. For this purpose, research results with respect to student learning of chemical equilibrium were used as input in the workshop. (A similar design was applied by Shymansky, Woodworth, Norman, Dunkhase, Matthews, & Liu, 1993.)
2. The following two or three meetings coincided with the implementation of the experimental course. These meetings were used both to discuss recent practical experiences as well as to prepare participants for topics following shortly after the meeting, in the way described above.
3. A final meeting was organized to reflect on experiences with the experimental course. In this meeting, teachers not only exchanged and discussed their personal experiences, but were also presented with specific results of our research. The latter was meant to fa-

Facilitate reflection on a theoretical level. Also, this meeting served to evaluate the experimental course. Therefore, participants were asked to fill in an evaluative questionnaire.

As one can see, the workshop was not designed to provide participants with checklists or recipes for the effective teaching of chemical equilibrium. Instead, adopting constructivist views, we tried to support and facilitate participants' construction of PCK by providing them with both practical experiences and results of research, and by organizing interactions between these two possible sources of knowledge construction.

The experimental course aimed at fostering conceptual change among students by (a) including assignments designed to challenge students' existing conceptions, and (b) stimulating active student engagement through small-group discussions and the execution of chemical experiments by students. This course design was based upon the assumption that for conceptions to be changed, dissatisfaction with existing conceptions is a prerequisite (Posner, Strike, Hewson, & Gertzog, 1982). Through small-group discussions facilitated by questions in the course material, students should try to explain phenomena conflicting with their initially held conceptions. Together, they should be able to solve the anomalies and reconstruct their conceptions. Obviously, the teacher has a crucial role in this design in helping students to overcome preconceptions and in guiding them toward conceptions that are chemically more valid.

From the teachers' perspective, this design also aims at developing their PCK. As teachers spend most of their time in classroom listening to and participating in student discussions, they are presented with opportunities to gain understanding of student reasoning, of their preconceptions and possible misconceptions, and of factors either promoting or hindering conceptual change. While taking part in student discussions, teachers can explore ways of explaining or representing subject matter. Reacting to student responses, they can expand their repertoire of approaches that may be effective for certain students in specific situations.

### *Research Method*

Applying a grounded theory approach (Strauss, 1987), our research project consisted of three consecutive research cycles. In this article, we focus on the in-service workshop that was part of the third and last cycle of our research. The workshop sessions were attended by 12 participants. All of them had an academic background in chemistry and more than 5 years of experience in teaching chemistry in upper-secondary education. As the topic of chemical equilibrium is a key subject in the national curriculum, all participants were familiar with this topic, both as a learner and as a teacher. All participants had chosen to attend to the workshop on a voluntary basis. Mostly, their choice was inspired either by interest in the topic or by the wish to innovate their educational practice. Most of the participants had previously taken part in similar workshops, for example, on the chemical reaction, electrochemistry, stoichiometric calculations, and the like. Some of them had previously been subjected voluntarily to research describing this as "an instructive experience."

All workshop sessions were recorded on audiotape. Additional data consisted of participants' written responses to assignments carried out during the sessions, and to the evaluative questionnaire. Moreover, during the implementation stage, audio recordings were made of classroom lessons of two of the participants. Finally, all participants collected and corrected the written responses of their students to the assignments in the experimental course. These written responses were handed over to the researchers.

The analysis of both types of audio recording was performed following a stepwise procedure. This involved the selection of fragments relevant with respect to teachers' subject-matter

knowledge or PCK. These fragments were transcribed verbatim and analyzed by the first and the third author. Researcher triangulation was aimed at by comparing and discussing interpretations of individual researchers until agreement occurred (Janesick, 1994). The validation of these interpretations was promoted by applying the constant comparative method (Denzin, 1994). This involved the comparison of the analyses of the transcripts with other sources, such as (a) chemistry schoolbooks, to trace the possible origins of teachers' representations of subject-matter, and (b) additional data, especially the written responses of both teachers and students that had been collected. In the first place, the analyses were aimed at constructing a picture of each teachers' conceptions and of possible changes in these conceptions. At a general level, the analyses resulted in theoretical notions with respect to the teaching and learning of chemical equilibrium.

### *Research Results*

This article is limited to research results concerning chemistry teachers' PCK of certain aspects of chemical equilibrium. Specifically, we will review the PCK participants held about the dynamic nature of chemical equilibrium on entering the in-service workshop, followed by a description of changes in some participants' PCK that were observed during the process of attending the workshop and implementing the experimental course. In relation to this, some relevant aspects of students' conceptual change processes will be described. Where appropriate, we will illustrate our results with fragments from the transcripts mentioned above. First, however, we will briefly sketch the educational context in which chemical equilibrium is being taught.

In The Netherlands, the introduction of the concept of chemical equilibrium usually takes place during the second year of chemistry education (cf. Grade 10). Previously, chemical reactions have been introduced as events in which the original substances disappear, while other, new substances are being formed. These conversions are accompanied by observable effects such as color changes or energy effects. Initially, chemical reactions are supposed to take place in one direction only and to proceed to completion as well. On the molecular level, substances are represented by molecular species. Molecules of the same species are considered identical; that is, they do not differ from each other in any way except position and motion (De Vos & Verdonk, 1987).

Some of these notions are challenged when the concept of chemical equilibrium is introduced. In the case of chemical equilibrium, the reaction under consideration does not proceed to completion, and appears to be reversible as well. Moreover, it is supposed that in a state of equilibrium, two opposite reactions take place at the same rate, although this cannot be deduced from direct observations. This so-called dynamic nature of chemical equilibrium is associated with many student problems and misconceptions (see e.g., Gussarsky & Gorodetsky, 1990; Camacho & Good, 1989; Banerjee, 1991; Quílez-Pardo & Solaz-Portolés, 1995).

The participants in our workshop appeared to consider this dynamic nature as a key element of chemical equilibrium. They reported that this aspect in particular was problematic for many students. Some participants described specific misconceptions similar to the ones described in the literature, although they were ignorant of this body of research. Moreover, most teachers themselves struggled with the abstract nature of the dynamic conception of chemical equilibrium, and its relation to observations during chemical experiments. This is illustrated in the following fragment of a discussion of five teachers with the first author during the first workshop session. The participants had been asked to react to the question of whether they think a forward and a backward reaction are taking place in a specific chemical system at equilibrium conditions.

*Transcript 1.*

- Teacher 1: I don't see it. I don't see a forward and backward reaction.
- Researcher 1: No, and you don't think a forward and a backward reaction are taking place in this situation as well?
- Teacher 1: Well, not necessarily.
- Teacher 2: Well, I do think so.
- Teacher 3: From my chemical knowledge and experience, I have no reason *not* to assume . . .
- Teacher 1: No, but can you see it?
- Teacher 2: No.
- Teacher 1: No, okay, then we agree about that.
- Teacher 4: I don't think it's logical from the experiments we've performed that under equilibrium conditions, a forward and a backward reaction are taking place.
- Teacher 3: It doesn't show from this experiment, but it simply follows from one's chemical experience.
- Researcher 1: You mean, during other experiments you've experienced that this is actually so?
- Teacher 3: During formal education, one is so much indoctrinated with this thesis; one is so used to speak in these terms and images, it became a fairly consistent story.
- Teacher 4: But then there is a big gap between you and your students, as they don't have that background. So, you fail good arguments from which follows: for this or that reason it is so. . . .
- Teacher 2: I could tell them a story about the energy distribution of molecules, but I cannot observe it. It doesn't show from anything, but it's logical.
- Teacher 5: I can explain it by assuming a dynamic equilibrium. That's the only thing. I cannot argue, however, why it really should be dynamic and not static.

As one can see from this fragment, these teachers lacked theoretical arguments to promote student understanding. They admitted that their usual arguments are weak and not very convincing for most of their students. The best they felt they could do was to demonstrate the dynamic equilibrium conception with the help of metaphors or analogies. In this respect, almost every participant appeared to have developed his or her own repertoire. Some of them used the analogies included in chemistry schoolbooks. Others had worked out their own analogies (cf. Thiele & Treagust, 1994). During the first session of the workshop, participants discussed the strengths and weaknesses of each other's favorite analogies. Common in these analogies was the representation of molecules by people or students or the attribution of human characteristics to molecules (e.g., "molecules don't fancy changing"). Remarkable in their discussion was that chemical validity seemed to prevail. Arguments from the students' perspective were barely noticed.

Following the first workshop session, participants implemented the experimental course in their chemistry classes. Clearly, the implementation process had a large impact on the teachers. Examples of this impact can most directly be observed in the transcripts of discussions of two of the participants with their respective students during the lesson series. In one of these discussions, Teacher 6 tried to clarify the dynamic nature of chemical equilibrium by comparing the equilibrium system with a classroom with two doors, through which students continuously move in and out. His explanation was interrupted by one of the students, who stated, "But that is not a chemical reaction!" Teacher 6 responded as follows: "No, you are right. But as this is about the disappearance and the appearance of particles, I can, of course, use people as well."

However, the students persisted in rejecting the teacher's analogy. During a discussion with the first author after this particular lesson, Teacher 6 asserted that the "incident" described above had made him realize the uselessness of his analogy, which had been an element of his PCK with respect to chemical equilibrium for some time. However, the incident had not provided him a new, more successful representation or strategy. Thus, in terms of conceptual change theory (Posner et al., 1982), although he had become dissatisfied with his present conception, he had not yet reached the stage of a new fruitful and plausible conception.

In another discussion, Teacher 7 initially did not recognize the arguments of his students. The students focused on the anomaly between a chemical system that does not seem to change and the idea that two opposite reactions are taking place continuously. Some of the students (Students 1 and 2; see Transcript 2) reasoned that they would expect the system to change from one state to another and back. However, these changes would then have to be accompanied by color changes corresponding to the students' observations during previous experiments, so that the system would resemble a traffic light. Teacher 7 presented several lengthy explanations to the students, but these apparently did not contribute to their understanding. The problem was eventually solved in the following fragment:

*Transcript 2.*

- Student 1: So it becomes blue, and then pink, blue, and pink again, all the time, doesn't it?
- Student 2: That would be fun. So it continues to react spontaneously?
- Student 3: Yes, but you cannot see it!
- Student 4: So the color stays the same, but there are a whole lot of wild events going on inside . . .
- Student 2: Oh! Now I see . . .
- Teacher 7: Exactly, on the inside. You got it! On the inside, the backward and the forward reaction keep taking place. But as they proceed at the same rate, you do not observe changes in the color.

After this lesson, Teacher 7 told the first author that it was only through the argumentation of Students 3 and 4 that he had eventually recognized the problem of Students 1 and 2. Until then, he had not explicitly discussed the idea that in this case the chemical reactions are taking place both simultaneously and unobservably, thus failing to address the students' problem. Through reflection on this discussion, this teacher's PCK was not only extended with knowledge of specific learning difficulties, but also with strategic knowledge of how to deal with these difficulties effectively.

The impact of experiences with the experimental course also emerged from teachers' reports during consecutive workshop sessions. As an example, the following transcript contains a fragment of a discussion recorded during the final workshop session. It illustrates how teachers can benefit from participating in small-group discussions with students.

*Transcript 3.*

- Teacher 8: For many students, the reaction is still one thing, not two.
- Teacher 9: It can either proceed forward or backward, but not in both directions at the same time.
- Researcher 1: It's hard to talk in terms of coinciding events, anyway.
- Teacher 10: One of my students had problems with the idea of reversibility. Sounding

very surprised, she said: "But I don't see it becoming pink, and then back to blue, and then pink again and back to blue again." She really missed the traffic light.

Researcher 3: The term "reversible" itself implies forward and backward.

Teacher 10: Forward and backward are separated in time. You can't be on your way to an island with a boat and at the same time go back, or something like that.

Researcher 3: You only go back after you've arrived.

Teacher 11: Still, it makes sense to discuss these ideas with students. That it would be like a traffic light if you could observe individual molecules. Such discussions may turn out to be very productive. At least, that's my experience. . . .

Teacher 12: For me, it was very instructive when a student reasoned that color of constant intensity was caused by different molecules all the time. His idea was that new molecules were continuously formed, but as the color remained unchanged, they had to be different molecules all the time.

Researcher 1: So he could relate the apparent static outside with the conception of reactions still taking place.

Teacher 12: Thus, he overcame the idea of forward and backward. But this was only in one group. But I could use this argument in other groups as well!

The last phrase in particular demonstrates an explicit extension of a teacher's PCK: An argumentation is added to his repertoire that has proved to be effective to promote conceptual change (cf. Teacher 7 in Transcript 2).

Transcript 3 also illustrates that the participants of the workshop, reflecting on their experiences with the experimental course, have recognized student problems similar to the ones mentioned earlier (e.g., Teacher 10). In fact, on the questionnaire evaluating the in-service workshop, many of them indicated that by listening carefully to students' reasoning their understanding of specific student conceptions had improved. Nevertheless, the participants reported both successes and failures with respect to the introduction of the dynamic equilibrium conception. About half of the participants indicated that this conception offered serious difficulties to their students. Some of them argued that their students refused to accept the possibility of unobservable reactions. Other teachers described students who persisted to reason in terms of only "one reaction" (cf. Teachers 8 and 9 in Transcript 3). On the other hand, however, participants claiming a successful introduction of the dynamic equilibrium conception often cited examples of productive student reasoning. They had discovered, for example, that students would reason that it was logical for both reactions to proceed, because all conditions for these reactions to take place were satisfied. Students used both macroscopic terms (e.g., "When all substances are present together, they will always react") as well as molecular terms (e.g., "Whenever molecules are present, they will collide, thus leading to reactions") in this respect.

From analyzing their answers to the evaluative questionnaire, it appeared that in particular, the participants' understanding of students' conceptions of molecules had deepened. When students discussed their ideas of molecules in relation to their observations of reversible and incomplete chemical conversions, the teachers had observed two types of reasoning. The first type of reasoning was described by one of the participants in terms of "students who put themselves in the position of one particle." Such students could not understand why some molecules may change whereas others remain intact. This type of reasoning hindered the acceptance of the dynamic equilibrium conception. In the second type of reasoning, however, students had introduced statistical notions in their molecular ideas. To illustrate this type of reasoning, one participant cited a typical student answer: "All particles will eventually change, but not at the same time."

The teachers' responses during the workshop sessions indicated that they had gained knowledge of specific types of students' reasoning and learning difficulties in the context of the introduction of chemical equilibrium. In addition, some reported to have extended their repertoire of successful strategies and representations with respect to this topic.

### *Discussion and Conclusions from the Empirical Study*

The results of the empirical study have contributed to our understanding of chemistry teachers' PCK with respect to chemical equilibrium. Specifically, elements of PCK were identified which differ considerably from the representations of chemical equilibrium commonly found in chemistry schoolbooks. Teachers succeeded in promoting conceptual change by discussing the anomalous results of certain chemical experiments with students. They challenged students' conceptions about chemical reactions by urging students to explain phenomena which indicate the reversibility and the incomplete conversion of chemical reactions. Thus, they provided students with a basis for the dynamic equilibrium conception to become an acceptable explanation of the anomalous experimental results. Many students indicated difficulties in accepting the idea of opposite reactions taking place simultaneously. Teachers could facilitate the process of overcoming this barrier by applying two different strategies:

1. They can discuss the possibility of continuous changes taking place at the molecular level. This implies an introduction of the element of time in the notion that molecules of the same species are identical. At a specific moment a molecule of Type X may be formed, while at the same time another molecule X at another place is converted. Thus, a statistical molecular image emerges in which the total amount of molecules X remains constant, but the collection consists of different molecules.
2. Because all conditions are satisfied for both the forward and the backward reaction to proceed, teachers can discuss the possibility of these reactions taking place observably, one after the other (traffic light reaction). As this possibility obviously conflicts with observations of the chemical system, one can proceed to assume that both reactions do proceed at the same rate, thereby canceling each other's observable effects.

Obviously, not every individual participant in our workshop reconstructed his or her PCK in the way described above. Instead, this description is constructed by the researchers through a synthesis of the research results with respect to individual teachers and students. In this way, we contributed to the first purpose for research on teachers' PCK mentioned earlier in this article: the increase of knowledge about the way teachers transform subject-matter knowledge and how they can relate their transformations to student understanding. Notably, this contribution is limited to the introduction of chemical equilibrium.

We have also added to the second purpose—that is, resolving a blind spot in preservice and in-service teacher education. The strategies we identified to successfully facilitate the introduction of chemical equilibrium are to be included in both types of teacher education. As the PCK teachers initially hold about chemical equilibrium appears to be inspired by current chemistry schoolbooks, fragments from these schoolbooks may be used to challenge teachers' conceptions. In particular, we suggest a critical discussion concerning the use of analogies and metaphors during the introduction of dynamic equilibrium. Contrary to Treagust, Duit, Joslin, and Lindauer (1992), we would hesitate to recommend the use of analogies to promote conceptual change. Next, teachers may be invited to perform and discuss chemical experiments commonly used in schoolbooks to introduce the idea of reversible reactions. Through these discussions, teachers' attention may be drawn to the occurrence of specific learning difficulties and misconceptions.

These can then be studied by providing both literature on specific research and authentic student responses. Preferably, examples must be included that illustrate typical ways of student reasoning: for example, the traffic light conception of a reversible reaction and the static conception of molecules, emerging from student questions such as "Why do some molecules react while others don't?" To simulate classroom practice, teachers may be asked to react to this type of student reasoning and to discuss their reactions mutually. Finally, the strategies described may be offered as possible approaches to stimulate students' conceptual change. Ideally, teachers should then be provided with opportunities to use these strategies in classroom practice and to reflect on their experiences.

### Concluding Remarks

In this final section, we return to the central topic of this article. Relating the results of our empirical study to the literature discussed earlier, we will discuss possible purposes for research on science teachers' PCK from a craft knowledge point of view.

As stated before, the literature discussed indicated that experienced science teachers' classroom practice is guided by a coherent and integrated set of knowledge and beliefs, within which conceptions about the teaching and learning of science play an important role. The content of teachers' conceptions appears to be rather traditional, particularly in terms of instructional strategies and goals. Therefore, science teachers' craft knowledge is often reported to hinder the innovation of science education. How do these findings relate to our introduction of the concept of craft knowledge in the beginning of this article? First, as the craft knowledge of science teachers actually differs from recent academic conceptions of teaching and learning, research on science teachers' craft knowledge may indeed lead to the establishment of an alternative knowledge base in addition to codified educational knowledge bases. Second, the understanding of science teachers' craft knowledge appears to be a vital source for in-service and preservice teacher education, especially when teacher education aims at improving science teaching practice. From the literature, it appears that specific workshops building on science teachers' craft knowledge actually succeed in promoting conceptual change among science teachers' knowledge and beliefs (e.g., Stofflett, 1994). Moreover, specific designs in which science teachers receive support or supervision may lead to gradual changes in classroom practice (e.g., Glasson & Lalik, 1993).

Shifting the focus of our discussion to PCK, we would like to call to mind a conclusion we drew from reviewing the literature on science teachers' PCK. So far, research on science teachers' PCK has focused on the nature and the development of PCK, rather than investigating science teachers' PCK with respect to specific topics. This research identified the importance of a thorough and coherent knowledge of subject matter and the necessity of teaching experience. Therefore, this research offers general guidelines for the design of teacher training programs aiming at the development of PCK. In particular, such programs should enable teachers to study the subject matter of specific topics from a teaching perspective. In this respect, teachers' subject-matter knowledge may be improved by studying the structure and evolution of students' ideas about particular topics (Shymansky et al., 1993). Furthermore, teacher training programs should provide opportunities to use PCK in teaching situations and to reflect on these practical experiences (Clermont et al., 1993).

Earlier, PCK was perceived as encompassing knowledge of representations of subject matter and understanding of specific learning difficulties and student conceptions with respect to specific topics (Shulman, 1986). From this conceptualization, we derived two main purposes for research on teachers' PCK, referring to the improvement of our understanding of the way teach-

ers transform subject-matter knowledge in relation to student learning and to the application of this understanding in the context of in-service and preservice teacher education. As stated above, we observed the absence of studies on science teachers' PCK with respect to specific topics. Our empirical study was presented as an example of such research. We argue that this type of study may significantly add to the value of the concept of PCK within the domain of research on science teaching. In our view, the value of PCK lies essentially in its relation with specific topics. Therefore, PCK is to be discerned from general pedagogical knowledge on the one hand, and from subject-matter knowledge per se on the other. As the results from our case study show, we have gained insight into the ways chemistry teachers transform their knowledge of chemical equilibrium to stimulate student understanding of this topic. The teaching strategies we identified are not useful in a universal sense, but refer exclusively to this topic. Still, as teachers teach specific topics, these strategies add a unique and valuable element to the educational knowledge base. Moreover, other teachers may benefit from this type of topic-related PCK as it can be used as input in preservice or in-service teacher education. In addition to the general guidelines identified above and analogous to the in-service workshop we conducted, we suggest that a course on topic-related PCK includes activities which invite teachers to (a) critically review schoolbooks, (b) perform scientific experiments, and (c) study authentic student responses. Through specific assignments and discussions, participants may be stimulated to integrate these activities and to reflect on both academic subject matter and on classroom practice. In this way, participants' PCK may be improved.

In the introduction to this article, we suggested that research on PCK can potentially be related to research on student learning. Studies of specific learning difficulties and student conceptions with respect to specific topics are of particular interest, since PCK encompasses understanding of these difficulties or conceptions. In our empirical study, we could indeed benefit from incorporating research on student learning of chemical equilibrium. In view of the vast amount of research on student conceptions and conceptual change with respect to specific science topics that has become available since the 1970s (e.g., Driver & Easley, 1978; Dykstra, Boyle, & Monarch, 1992; Vosniadou, 1994), we would welcome studies on the same topics from the teachers' perspective. Specifically, studies focusing on teachers' representations and instructional strategies to overcome student misconceptions and to promote conceptual change would add to the knowledge base of science teachers' PCK.

Finally, we remind the reader of the controversy concerning the question whether research on teachers' craft knowledge, including PCK, would have to be limited to idiosyncratic descriptions (Tom & Valli, 1990). We think that both the discussion of the literature and the empirical study demonstrate that research on science teachers' craft knowledge or PCK may indeed surpass the individual level and generate knowledge of a more general nature instead. For example, through generalization from the results of the empirical study, patterns of instructional strategies with respect to chemical equilibrium were deduced. This does not imply, however, that every teacher participating in the study has incorporated these strategies in his or her PCK. Consistent with some findings in the literature (Lantz & Kass, 1987; Leinhardt & Smith, 1985), considerable differences between teachers' craft knowledge may occur at the individual level even if their academic knowledge and their educational contexts are similar. Besides, teachers develop their craft knowledge in different ways. For example, participation in our workshop has had serious impact for some teachers, while others' PCK apparently was hardly affected. As for us, this is an essential implication from the adoption of a craft knowledge perspective. Instead of generating checklists with indicators of effective instruction, we aim at providing teachers with a knowledge base which enables them to teach specific topics effectively and flexibly in situations that are subjected to different contextual, situational, and personal influences. We

think that PCK with respect to various specific topics constitutes a vital element of this knowledge base.

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