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Abstract: In this article, we describe the results of a study of the pedagogical content knowledge (PCK) of preservice chemistry teachers in the context of a postgraduate teacher education program. A group of preservice teachers ($n = 12$) took part in an experimental introductory course module about the use of particle models to help secondary school students understand the relationship between phenomena (e.g., properties of substances, physical and chemical processes) and corpuscular entities (e.g., atoms, molecules, ions). The module emphasized learning from teaching by connecting authentic teaching experiences with institutional workshops. Research data were obtained from answers to written assignments, transcripts of workshop discussions, and reflective lesson reports, written by the participants. The outcomes of the study revealed that, initially, all participants were able to describe specific learning difficulties, such as problems secondary school students have in relating the properties of substances to characteristics of the constituent particles. Also, at this stage, all preservice teachers acknowledged the potential importance of using models of molecules and atoms to promote secondary school students' understanding of the relationship between phenomena and corpuscular entities. After teaching, all preservice teachers demonstrated a deeper understanding of their students' problems with the use of particle models. In addition, about half of the participants had become more aware of the possibilities and limitations of using particle models in specific teaching situations. Through learning from teaching, the preservice teachers further developed their PCK of using particle models, although this development varied among preservice teachers studied. © 2005 Wiley Periodicals, Inc. J Res Sci Teach 42: 947–964, 2005

Shulman introduced pedagogical content knowledge (PCK) as teachers' ''own special form of professional understanding'' (Shulman, 1987, p. 8); that is, as a form of teachers' (professional) practical knowledge (Van Driel, Verloop, & De Vos, 1998). This implies that PCK is something beginning teachers can hardly learn from a textbook, or a short course only. To develop PCK, teachers need to explore instructional strategies with respect to teaching specific topics in practice.

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Also, they need to gain an understanding of students' conceptions and learning difficulties concerning these topics (Lederman, Gess-Newsome, & Latz, 1994). However, so far, not much is known from research about the process of PCK development among beginning teachers, and how this development may be facilitated. Clearly, understanding of the development of PCK is necessary to design effective teacher education programs. The purpose of the present study was to contribute to this area of research. We focused on the development of preservice chemistry teachers' PCK in the context of a 1-year postgraduate program, consisting of a combination of institutional activities and authentic teaching experiences, aimed at obtaining a qualification for teaching chemistry in upper secondary schools in The Netherlands.

In the present study, the focus was on an important topic in teaching chemistry, namely, the use of particle models to understand the relationship between phenomena (e.g., properties of substances, physical and chemical processes) and corpuscular entities (e.g., atoms, molecules, ions). Although there have been several studies of secondary school students' conceptions in this area (e.g., Harrison & Treagust, 1996), according to Justi and Gilbert (2002), little is known about teachers' knowledge of this topic, and how it is developed. In what follows we first discuss the literature on two important elements of our study: the nature and the development of pedagogical content knowledge, on the one hand, and the role of particle models, on the other. Next, we describe the research context, focusing on the design of a specific teacher education course module. Finally, we assess the empirical part of the research project.

Nature and Development of Pedagogical Content Knowledge

Elaborating on Shulman's work, various scholars have proposed different conceptualizations of PCK, in terms of the features included or integrated (Grossman, 1990; Marks, 1990). Some describe PCK as a "mixture" of several types of knowledge needed for teaching, whereas others explain PCK as the "synthesis" of all knowledge elements needed in order to be an effective teacher (cf. Cochran, DeRuiter, & King, 1993). Magnusson, Krajcik, and Borko (1999) presented a strong case for the existence of PCK as a separate and unique domain of knowledge. In any case, PCK, referring as it does to specific topics, is distinct from general knowledge of pedagogy, educational purposes, and learner characteristics. Moreover, because PCK is concerned with the *teaching* of specific topics, it may differ considerably from the subject matter knowledge of these topics. However, several investigators have pointed out that it is not always possible to make a sharp distinction between PCK and subject matter knowledge (Marks, 1990; Tobin, Tippins, & Gallard, 1994). Loughran et al. (2001) defined PCK as "the knowledge that a teacher uses to provide teaching situations that help learners make sense of particular science content" (p. 289). They argued that investigations of PCK should avoid reducing PCK to a mechanistic, technical description of teaching, learning, and content. To capture the complexity and diversity of science teachers' PCK, these investigators developed for specific topics, such as the human circulatory system, a combination of a content representation together with a series of so-called PaP-eRs (pedagogical and professional-experience repertoires). This approach should serve to help experienced teachers to make explicit parts of their tacit knowledge, thus enhancing their understanding of their own practice. In science teacher preparation programs, this approach may support preservice teachers in better linking teaching and learning in meaningful ways for secondary students (Loughran, Mulhall, & Berry, 2004).

Magnusson et al. (1999) conceptualized PCK as consisting of five components: (a) orientations toward science teaching; (b) knowledge of the curriculum; (c) knowledge of science assessment; (d) knowledge of science learners; and (e) knowledge of instructional strategies. In the present study, the focus was on the two latter components. In our view, knowledge of science learners concerns student learning of a specific topic and comprises knowledge of students' learning difficulties, whereas knowledge of instructional strategies includes knowledge of representations (e.g., models, metaphors) and activities (e.g., explications, experiments) for teaching a specific topic. These components are intertwined and should be used in a flexible manner: The better teachers understand their students' learning difficulties with respect to a certain topic, and the more representations and activities they have at their disposal, the more effectively they can teach about this topic.

In the literature on PCK, various suggestions can be found on how to promote the development of preservice teachers' PCK in the context of teacher education programs. For instance, Magnusson et al. (1999) argued that the development of PCK is a complex process, which is determined, among other things, by the nature of the topic, the context in which the topic is taught, and the way a teacher reflects on teaching experiences. These investigators concluded that a teacher education program can never completely address all the components of PCK a teacher needs. Grossman (1990) identified four major sources of PCK development: (a) disciplinary education, which naturally constitutes the basis for subject matter knowledge and, consequently, constitutes the basis for knowledge of representations (e.g., analogies and examples) for teaching; (b) observation of classes, which may promote preservice teachers' knowledge of secondary students' learning difficulties; (c) classroom teaching experiences, which may promote preservice teachers' knowledge of topic-specific teaching activities, such as demonstrations and investigations; and (d) specific courses or workshops during teacher education, which have the potential to affect PCK, such as by extending preservice teachers' knowledge of specific representations, or their knowledge of secondary students' learning difficulties.

However, as there have been few studies of the ways PCK develops over time, the relative impact of each of these four factors is not clear. It seems that the most important contributions are made by disciplinary education (Sanders, Borko, & Lockard, 1993) and classroom teaching experiences (Van Driel, De Jong, & Verloop, 2002). To enhance the impact of classroom teaching experiences, preservice teachers should be stimulated to reflect on their own teaching (Osborne, 1998). Connecting teaching experiences with reflections can promote new insights into the teaching of specific topics, and thus can contribute to the reframing and revising of teachers' own practice (Bryan & Abell, 1999). In addition, we recommended, on the basis of a previous study (Van Driel et al., 2002), the organization of field-based activities in such a way that they promote preservice teachers' understanding of their students' conceptions and learning difficulties; for instance, by asking them to analyze students' responses to written tests or interview questions (cf. Morrison & Lederman, 2003).

As for institutional activities within teacher education programs, their impact on PCK development is either unknown or not large (Smith & Neale, 1989), although Clermont, Krajcik, and Borko (1993) claimed a significant improvement as a result of a specific workshop.

Although the existing literature on PCK does not provide us with a complete and coherent research-based theoretical framework, we drew the following guidelines from this literature with respect to the design of a course module aimed at the development of preservice teachers' PCK. First, institutional activities can be aimed at explicating and expanding preservice teachers' knowledge of secondary students' conceptions and learning difficulties, and may also help to stimulate their thinking about specific instructional strategies in this area. Next, preservice teachers should be given opportunities to experiment with teaching strategies in authentic classroom situations. Preferably, they should also collect data from students (e.g., by analyzing students' answers to written tests) in this context. Finally, preservice teachers should be stimulated to reflect on their practical experiences, both individually and in group settings.

In a later section, we discuss in more detail how these guidelines were applied in the design of an experimental course module about the use of particle models to help secondary school students understand the relationship between observable phenomena and their interpretations in terms of corpuscular entities in chemistry education. In the empirical study, the focus was on the development of PCK that actually occurred in the context of this module. First, we briefly discuss the role of particle models in chemical education, which constituted the module's topic.

The Use of Particle Models to Understand the Relationship Between Phenomena and Corpuscular Entities

Many meanings are attached to the notion of models. Generally speaking, a model in science may be defined as a non-unique, partial representation of a target, focusing on specific aspects of it, whereas other aspects of the target are deliberately excluded (Ingham & Gilbert, 1991). The term "target" refers to, for instance, a system, an object, a substance, or a process. In the second half of the last century, the production and use of models played a central role in the growth of chemical knowledge (Luisi & Thomas, 1990). Thinking and reasoning with models enables chemists to visualize the abstract processes and entities they are investigating (Justi & Gilbert, 2002). Most notably, particle models have become very important in chemistry. Leading chemists, such as Pauling, and Watson and Crick, used concrete models to speculate about the spatial arrangement of atoms and functional groups in molecular structures, and to predict the properties of substances (Francoeur, 1997). Chemists often use models without being aware of it. They may, for instance, "jump" from the world of corpuscular entities to the level of macroscopic phenomena, and back, in a flexible and implicit way (Johnstone, 1993). Although this may not be problematic in the context of communication between chemists, it may easily lead to misunderstanding in the context of chemistry education. According to De Vos and Verdonk (1987), the chemist's knowledge of particle models contributes much to the communication gap between chemistry teachers and their students in secondary education, resulting, among other things, in students feeling alienated from the world of chemistry. For secondary students, the conceptual demands of switching between models and phenomena can be overwhelming (Andersson, 1990).

Harrison and Treagust (1996) investigated students' (grades 8–10) understanding of models of atoms and molecules. They found that most students preferred models of atoms and molecules "that depict these entities as discrete, concrete structures" (p. 532). Similar results were obtained by Ingham and Gilbert (1991). Other scholars found that secondary students attribute macroscopic properties to atoms or molecules, for instance, reasoning that water molecules are wet, or that sulfur atoms are yellow (De Vos & Verdonk, 1996). These results have been interpreted in the light of secondary students being inexperienced with the use of scientific models, and their lack of "intellectual maturity" (Harrison & Treagust, 1996, p. 532).

Chemistry textbooks for secondary education, obviously, contain many examples of models, mostly particle models. However, these models are often presented as static facts or as final versions of our knowledge. Contrary to the suggestions of Harrison and Treagust (1996) and others, their status and limitations, or the way they were developed, are seldom addressed. Moreover, textbooks rarely include assignments inviting secondary students to actively use particle models for relating observable phenomena to corpuscular entities (Erduran, 2001). Consequently, given the dominant role of textbooks in science teaching, we expected that preservice chemistry teachers would not be used to including such activities in their practice. Moreover, given their training as chemists, we expected preservice teachers of chemistry to deal with particle models in an expert way. This implies that they may use such models, for instance, when trying to explain certain chemical phenomena, in a flexible, implicit way, without being aware of possible problems in the communication with secondary students (cf. Gabel, 1999). In any case, preservice chemistry teachers need to develop PCK of using particle models to help secondary students understand the relationship between phenomena and corpuscular entities. However, according to Justi and Gilbert (2002), in their overview of the specific role of models and modeling in chemical education, ''there have been very few initiatives to promote the development of teachers' pedagogical content knowledge in this area'' (p. 57). This was the focus of the present study. We aimed to contribute to a research-based practice of PCK development by addressing the following general research question: *How does preservice teachers' PCK of the use of particle models develop in the context of a specific course module within a chemistry teacher education program*? The specific research questions that guided this study were:

1. What is the content of preservice teachers' initial PCK of learning difficulties concerning the use of particle models?
2. What is the content of preservice teachers' initial PCK of instructional strategies they consider useful to overcome such learning difficulties?
3. What is the content of preservice teachers' PCK after participating in the course module, including teaching a series of lessons about the use of particle models to help secondary school students understand the relationship between phenomena and corpuscular entities?

Methods

Context of the Study

The present study was situated in the context of a 1-year postgraduate teacher education program, qualifying participants for the teaching of chemistry at the pre-university level (cf. grades 10–12 of secondary education). Before entering this program, the participants had obtained a master's degree in chemistry. During the entire program, the preservice teachers (PTs) worked at practice schools (teaching about five to ten lessons per week). They also took part in institutional workshops (two afternoons per week, on average), and reported and reflected on their teaching experiences and discussed their findings with each other. An experimental course module was developed, which aimed at learning to use particle models to help students in secondary education understand the relationship between observable phenomena and corpuscular entities. For the participants, the module was the first one on this issue, and, for this reason, it could be considered as an ''introductory'' module. This module was scheduled to take place about halfway through the teacher education program over a period of about 10 weeks.

Participants

The participants in this study were a group of 12 (3 female, 9 male) preservice teachers of chemistry. In the spring of 2000, eight PTs followed the institutional program at Utrecht University, while the other four participated in the program at Leiden University. The experimental course module was taught by two different teacher educators, the first author of this article being the instructor at his own university. A written protocol was developed in advance to ensure that the module would be taught as similar as possible at both universities. The protocol consisted of a series of detailed workshop plans: For each workshop a description was given in terms of the learning goals, the teaching and learning activities, their planning and timing, the resources needed, and so on. To make sure that the PTs at both universities received the same instructions, all assignments were presented in written form to them. During the period when the module was carried out, authors and instructors met several times and, in addition, contacted each other through e-mail and by phone to monitor the progress of the module at the two universities. In this way, it appeared to be possible to teach the module according to the written protocol, without having to make alterations at either of the two universities.

Instructional Design and Data Collection

The course module focused mainly on offering opportunities for learning *from* teaching, rather than learning *of* teaching. The latter approach assumes that preservice teachers learn in a mainly passive way how to teach, whereas learning *from* teaching means that preservice teachers learn in an active way, involving real practice situations, to make their learning more meaningful to themselves (cf. Lampert & Loewenberg, 1998). Our choice of this perspective on learning implies that the PTs were not asked, for instance, to read in advance scholarly articles about secondary school students' difficulties and possible teaching strategies in chemistry education. Instead, the idea was to develop preservice teachers' PCK according to the guidelines from the literature described earlier; that is, by first explicating their existing PCK and then expanding it, through discussing current secondary school textbooks; next, by teaching and collecting classroom data about students' conceptual difficulties; and, finally, by reflecting on their teaching practice. This design can be categorized within the group of "interactive models" of teachers' professional development (Sprinthall, Reiman, & Thies-Sprinthall, 1996), and requires strong linkages between institutional activities and classroom practice. The module was designed according to these ideas and is described in what follows.

To monitor the development of PCK during the module, data were collected at specific moments that were closely associated with the design of the course module (cf. Baxter & Lederman, 1999). The data collected consisted of: (a) the written answers of each individual preservice teacher to the questions and assignments included in the four parts of the module; (b) the reflective lesson reports written by the PTs at the end of the module; and (c) the audiotape recordings of all plenary discussions that took place during the institutional workshops. These recordings were transcribed verbatim. In addition, lessons about the self-chosen topic were audiotaped by the PTs themselves.

Procedures and Research Instruments

In this section, the instructional design is discussed in more detail. The focus is on the instructions and assignments that were also used to collect data on the participants' PCK. The *first* part of the module aimed at making the PTs (more) aware of their existing PCK, especially with respect to difficulties in understanding the relationship between corpuscular entities, and substances or processes. During a workshop session, they were asked to answer the following question:

> *Assignment 1*: What difficulties in learning the relationship between corpuscular entities and substances or processes do you remember from your earlier experiences as a schoolboy or -girl and as a university student, or from your previous teaching practice?

The PTs wrote down their recollections individually, which were then discussed by all. All written answers were collected, and the plenary discussion was audio-recorded and transcribed.

The *second* part of the module aimed at expanding preservice teachers' PCK in preparation for classroom teaching. During a workshop, the PTs were asked to select and read relevant parts of school textbooks. In particular, they read and discussed three sections of a chapter on molecules and atoms, and their relationship with substances and processes, taken from a current chemistry textbook for grade 9 (age 14–15) (Pieren et al., 1995, pp. 188–198). The PTs had no prior experience in teaching these sections. The sections covered the following basic issues: (a) substances are supposed to be composed of molecules; molecules cannot be observed; (b) the (physical) process of phase transition is explained in terms of molecules; and (c) the (chemical) process of reacting substances is described in terms of rearranging atoms. For the latter purpose, Dalton's model of the atom was used. Preceding a plenary discussion about these sections, the PTs were asked to write down individually their responses to the following assignment:

> *Assignment 2*: (a) What students' difficulties in understanding these issues do you expect? and (b) Give some examples of instructional strategies that you may use to promote students' understanding of these issues.

Again, all written responses were collected, and the following plenary discussion was recorded on audiotape and transcribed.

The *third* part of the module aimed at further promoting preservice teachers' PCK by inviting them to design and teach a series of lessons on a topic focusing on the use of particle models to understand the relationship between phenomena and corpuscular entities. For this purpose, they could choose one of the three issues that were discussed before, but, because of the constraints of the teaching programs at their practice schools during this part of the module, the PTs were allowed to choose any other relevant topic as well. Although teaching programs differed from school to school, every preservice teacher was able to choose a relevant topic (e.g., differences in the boiling points of alkanes in relation to the structures of alkane molecules; differences in solubility and boiling points in relation to intermolecular hydrogen bridges; the rate of chemical reactions in relation to the characteristics of particles; and electrochemical phenomena and their explanations in terms of corpuscular entities). Each preservice teacher taught three to six lessons on the chosen topic at his or her practice school, using the current textbook, and made audio-recordings of these lessons.

The *fourth* part of the module aimed at making the PTs aware of the PCK they had developed after, and as a result of, teaching. They were asked to write an individual reflective report about difficulties in teaching and learning, and about new teaching intentions, using the following guidelines:

> *Assignment 3*: Write a concise report about the most remarkable episodes and events during the lessons, including the analysis of the students' mistakes in a test at the end of the lessons. Address the following issues: (a) What difficulties of students did you identify?; (b) What difficulties did you experience in your teaching?; and (c) What changes would you make in these lessons next time?

During a final workshop, these reports were presented and discussed plenary. All written reports were collected and, again, the concluding plenary discussion was recorded on audiotape and transcribed verbatim.

Data Analysis

The analysis of the data focused on the written answers of all preservice teachers to Assignments 1 and 2, plus their reflective lesson reports (Assignment 3), in combination with the audio-recordings of the plenary discussions related to these assignments. The data were analyzed from an interpretative phenomenological perspective (Smith, 1995), without the use of an a priori–established system of categories or codes. Data collected during various parts of the module were analyzed in relation to the three specific research questions. Regarding the first research question, a distinction was made between remembered and expected learning difficulties. The former subquestion was answered on the basis of an analysis of the written responses to Assignment 1 (see earlier), in combination with the transcribed audio-recording of the associated plenary discussion. For the latter subquestion, the written answers to Assignment 2, part a, were analyzed, in combination with the transcription of the related workshop discussion. To answer the second specific research question, the preservice teachers' written responses to Assignment 2, part b, were analyzed, together with the transcribed audio-recording of the plenary discussion which followed that assignment. Finally, the answer to the third specific research question was obtained by analyzing the reflective lesson reports (Assignment 3), combined with the transcription of the concluding plenary discussion. As we were interested in the teachers' knowledge, rather than in their classroom behavior, the audio-recordings of the lessons taught by the PTs were used as additional data, mainly serving to improve our understanding of the context in which they had taught their lessons and had written their reflective reports.

For each research question, the process of data analysis consisted of a similar multistep procedure. As a first step in this procedure, the written responses to the assignments, and the transcriptions of the related workshop discussions, were analyzed for each individual preservice teacher by the first and second authors individually. For this purpose, individual contributions to plenary group discussions were combined with the written responses of the respective individual PTs. Next, by comparing and discussing our individual analyses (investigator triangulation; Janesick, 2000), we aimed to reach consensus about the interpretation of the data in terms of the content of each individual preservice teacher's PCK. Depending on the specific research question, PCK was interpreted in terms of either knowledge of learning difficulties, or knowledge of instructional strategies, prior to, or after, teaching the lesson series. Moreover, specific categories emerged during this part of the analysis. For instance, in the case of the first research question, it appeared that the data could be classified as either referring to learning difficulties associated with the relationship between corpuscular entities and phenomena, or to the characteristics of corpuscular entities. Finally, for each research question, the content of the PCK was compared across all the PTs and discussed by the first and second authors. This step was aimed at finding similarities or patterns in the content of the PCK of various PTs, leading to the identification of subgroups of teachers with similar PCK (in the case of the second and third research questions). For instance, in the case of the third research question, two subgroups of PTs could be identified, whose PCK focused either on observed learning difficulties or on instructional strategies.

Findings

Throughout this section, we refer to PTs using names that are different from their real names. Female names, however, refer to female teachers and male names to male teachers. The four PTs from Leiden University were named Rosie, Joni, Pete, and Joe. Thus, the other names refer to PTs from Utrecht University.

Specific Research Question #1: *What is the content of preservice teachers' initial PCK of learning difficulties concerning the use of particle models?*

This research question is discussed in the following two subsections, which address the learning difficulties remembered both as learners and as preservice teachers, and expected learning difficulties.

Preservice teachers' initial PCK with respect to learning difficulties (1): From personal memories and observations. During the first part of the module, nearly all PTs reported remembering difficulties in learning about the relationship between corpuscular entities and substances or processes from their earlier experiences as school-boys or -girls, and as university students, or from their previous teaching practice (Assignment 1). Their answers were classified in two categories of learning difficulties, referring to: (a) the relationship between corpuscular entities and substances or processes; and (b) the characteristics of corpuscular entities. A distinction was also made between personal learning difficulties and observed secondary students' learning difficulties.

The PTs used specific examples to illustrate remembered learning difficulties. Regarding category (a), the relationship between corpuscular entities and substances or processes, they gave a variety of examples; for instance:

> Relating temperature to the speed of particles. Temperature is a function of the speed of particles. . .difficult. [Wayne, workshop discussion]

or:

> A molecule, you know, it is a particle. But yes, okay, a substance does specific things, it explodes, it reacts, it does something, but a molecule, it does nothing, only when there are more than one. Yes, okay, hard to understand for me as a school-boy. [George, workshop discussion]

Examples of observed secondary students' learning difficulties included:

> Molecular model provides hard balls with sticks. How to combine with the visible world, that is hard for students. [John, written answer]

and:

> Difficulties in understanding decolorizing of a liquid with active carbon (macro) by using a model of particles at a surface. [Rick, written answer]

Regarding category (b), the characteristics of corpuscular entities, nearly all examples concerned the invisibility of such entities; for instance:

> I could hardly imagine anything with respect to particles. . .for instance, a wooden table consists of particles, but I do not see particles at all. [Robert, personal learning difficulties; workshop discussion]

and:

> Difficulties in understanding nonvisible things. [Jim, observed students' learning difficulties; written answer]

During the workshop discussions, the PTs indicated that they had forgotten much about learning difficulties from their earlier experiences as school-boys or -girls, and as university students. They also pointed out that they had not observed many students' learning difficulties during their teaching practice so far.

Preservice teachers' initial PCK with respect to learning difficulties (2): From textbook analyses. During the second part of the module, the PTs wrote and discussed learning difficulties they expected with respect to secondary students' understanding of several issues described in the three sections of the textbook chapter under consideration (Assignment 2, part a). Although their written answers showed a variety of learning difficulties, most of these could be classified in the same categories as those just presented. Regarding category (a), the relationship between corpuscular entities and processes, a preservice teacher expected:

> The connection between molecular theory and phase transitions will be hard to understand. For instance, vaporization of water, molecules escaping from it, they release themselves from the surface of the liquid. Are these molecules in the vapor? That will be difficult for students to imagine. [Robert, written answer]

Another example in this category concerned the relationship between corpuscular entities and the process of chemical reactions, and was given by another preservice teacher as follows:

> Suppose, there is a reaction with oxygen. During this reaction, the oxygen molecules split up. Something changes. But they have learnt that oxygen is a nondecomposable substance, the molecules of which consist of one kind of atoms. So, the substance is nondecomposable, but, during the reaction, the molecules break up. That is very strange. It appears to be possible to be nondecomposable, but also to be involved in a reaction. [George, workshop discussion]

Regarding category (b), the characteristics of corpuscular entities, most of the learning difficulties were described as cognitive conflicts. For instance, one preservice teacher expected the following difficulty for secondary students when they would have to relate corpuscular entities to substances:

> They will not understand why molecules move, while the substance does not move. [Jim, written answer]

During the plenary discussion about their written answers, the PTs endorsed the reported difficulties. Moreover, at the end of the discussion, they agreed about a general student conception underlying many of the specific difficulties; that is, the conception that particles are the smallest parts of a substance that still have all the properties of this substance. They considered this student conception as an important cause of the learning difficulties they expected.

Specific Research Question #2: *What is the content of preservice teachers' initial PCK of instructional strategies they consider useful to overcome such learning difficulties?*

After focusing on expected learning difficulties, the PTs wrote down and discussed instructional strategies that they considered potentially useful to enhance students' understanding (Assignment 2, part b). Half of the sample (Jim, Wayne, Harry, John, Joni, and Rosie) wrote that they would hardly change the content and the structure of the textbook considering the topic under consideration (i.e., molecules and atoms to explain phase transitions and chemical reactions; grade 9). However, the other half of the sample (Robert, Ann, Rick, George, Pete, and Joe) intended to adapt the structure of each textbook section to prevent possible confusion among students. Specifically, they would prefer to start from the corpuscular perspective, rather than from the macroscopic perspective, as is done in the textbook. As one of them wrote:

> In the textbook, theory and practice are very strongly integrated. It should be split up much more to prevent confusion among students. I would prefer theory first, followed by examples of phenomena. [Robert, written answer]

During subsequent workshop discussions, the PTs talked about the possibility of using particle models during their teaching. For instance, when talking about the Law of Conservation of Matter, one of them said:

> Regarding the conservation of matter, I would like to use models to demonstrate that atoms do not disappear during chemical reactions. [George, workshop discussion]

Another preservice teacher talked about isomerism of substances. He said:

> I would discuss differences between substances with the same formula, such as butanol and ether, by showing molecular models of these isomers. [Harry, workshop discussion]

All PTs concluded that they would teach the relationship between corpuscular entities and substances or processes using models of molecules and atoms to promote their students' understanding.

Specific Research Question #3: *What is the content of preservice teachers' PCK after teaching a series of lessons about the use of particle models?* In this section, the focus is on the preservice teachers' PCK of using particle models as it could be characterized from their reflective reports (Assignment 3), and discussions during the final workshop. Seven PTs reported mainly on the learning difficulties of their students, whereas the other five PTs focused mainly on instructional strategies. However, the latter group of PTs also, to some extent, reported on learning difficulties. The distinction between a focus on learning difficulties, and a focus on instructional strategies was used to organize the findings in this section.

Preservice Teachers Focusing on Observed Learning Difficulties

In their reflective reports, seven PTs (George, John, Joni, Rosie, Joe, Pete, and Wayne) mainly described the learning difficulties of their students concerning the use of particle models to understand the relationship between corpuscular entities and phenomena. Their descriptions of specific learning difficulties varied considerably in terms of details and precision. The most detailed descriptions of such difficulties were presented by George and John. George focused on the use of particle models to explain the relationship between properties of substances (i.e., the boiling points of alkanes) and corpuscular characteristics (i.e., the strength of bonding between molecules). He asked his students (grade 10) to build models of the respective molecules. On the basis of a detailed account of their responses, George identified specific learning difficulties associated with confusion about the structure of the molecules (size vs. shape) in relation to the boiling points of the corresponding substances. George concluded that, although building the models had helped the students to visualize the structure of the molecules, the relation with properties of substances was not evident to them. During the final workshop, he elaborated on these findings. He described some problems he observed during a lesson:

> As for water, they think it consists of a hydrogen molecule plus an oxygen atom, or sometimes also an oxygen molecule. They mix it all up. [. . .] And when they argue that, for water, the particles consist of atoms, then they deny that, in the decomposition of water, it is possible that molecules be released. To them, only atoms can be released. [George, final workshop]

In a similar way, John focused on students' use of particle models to understand phenomena such as boiling points and solubility in relation to corpuscular characteristics. He concluded that it is very difficult for most students (grade 10) to relate the world of observable phenomena to the corpuscular world. In his reflective report, he suggested that these problems might be caused by the abstract nature of the particle world, and, therefore, he recommended the use of visualizations to overcome these difficulties. Thus, he formulated teaching intentions to overcome the observed difficulties.

Other preservice teachers reported on learning difficulties in more global terms. Two discussed some responses of their students they had remarked during lessons. Joni taught about hydrogen bonding to explain the macroscopic properties of water (grade 10), and concluded that this issue was ‘‘too abstract for the students, which made them lose their motivation.’’ [Joni, reflective report]

Consequently, she formulated the intention to pay attention to the relation between ‘‘micro’’ and ‘‘macro’’ in a more consistent way. However, she did not refer to strategies in relation to the use of particle models for this purpose. Another preservice teacher, Rosie, practiced modeling activities with her students (grade 9). She concluded that building models had helped her students to understand the difference between molecules and atoms. Moreover, she noted that most students had serious problems in relating these models to observable phenomena, such as the boiling of water and the decomposition of substances. Rosie did not formulate specific teaching intentions.

Finally, three other PTs (Joe, Pete, and Wayne) also reported mainly on learning difficulties. They focused in particular on their students' answers to a written test about the characteristics of molecules (grade 9), or reaction rates in relation to the model of colliding particles (grade 10). In their reports, they discussed the answers in terms of wrong or correct, and concluded that most students experienced difficulties in relating particles to phenomena. One of them reported:

> Linking visible processes and the related behavior of particles is difficult for students. To them, these are two different issues; for instance, higher temperature versus particles moving faster. [Joe, reflective report]

One of the others suggested that maybe:

> Students are not enough aware that they need to reason at two levels: micro and macro. [. . .] They give answers such as ‘‘The concentration of HCl increases, therefore, the reaction rate increases.’’ They forget to incorporate particles and collisions as an intermediate step in their reasoning. This is the cause of most of their mistakes. [Wayne, reflective report]

Preservice Teachers Focusing on Instructional Strategies

In their reflective reports, five PTs (Harry, Jim, Robert, Ann, and Rick) mainly focused on their instructional strategies. Their reports also contained accounts of the students' responses to this approach. Harry described activities with particle models he conducted in a class of grade 10. He asked students to build molecular models, giving them assignments in the form of a quiz or a puzzle (e.g., ‘‘Build two different molecules of a set of five different atoms, one of which is a carbon atom’’), to make these more challenging. Harry concluded that this model-building assignment motivated his students, much more than giving them detailed instructions. After the students had built molecular models of isomers of 2-butene, he also asked them whether specific isomers represented different substances, with different macroscopic properties, but according to Harry's reflective report, ‘‘they couldn't answer this question.’’

Another PT, Jim, developed a series of lessons for grade 9 about the atomic model of Rutherford. In his report, a detailed account of the design of this series of lessons was presented, including the questions he asked the students at certain moments, and why he asked these questions. He also described his students' responses to his teaching approach. In particular, he focused on the role of the Rutherford model in promoting understanding of the relation between specific phenomena (i.e., the historical experiments in which gold foil is subjected to a beam of helium gas), and the structure of atomic entities. To explain the experimental results, he introduced a model of an atom, consisting of a nucleus, surrounded by an electron cloud. Then he asked the students, ''What is between the nucleus and the electrons?'' The students answered, ''Air.'' Having expected this confusion between substances and corpuscular entities, Jim elaborated on the model, discussing the relative sizes of the electron cloud and the nucleus, and introducing the idea of the nucleus consisting of protons and neutrons. However, he concluded that, for some students, the idea that an empty space should be filled with ''air'' remained attractive. During the final workshop, he elaborated on this issue. He said that some students reasoned that if an atom is for the most part ''empty,'' then one should be able to see right through, for instance, gold foil. These experiences contributed to Jim's understanding of students' reasoning and also stimulated his thinking about useful teaching strategies.

Yet another PT, Robert, used particle models in the context of balancing reaction equations (grade 9). In a step-by-step account, he described, in his reflective report, how this approach was designed, and how his students responded to it. In this way, he was able to identify specific difficulties of his students, and, in relation to this, weaknesses in his approach. He concluded that using the models had been helpful only in certain steps (e.g., counting the atoms within each molecule), whereas using these models had confused his students in other steps (e.g., using the model to balance the number of atoms on both sides of the reaction equation arrow). Consequently, he formulated the intention to pay extra attention to the selection and use of particle models when preparing his teaching, and to monitor carefully their effectiveness in promoting students' understanding during the lessons.

Ann taught about electrochemical cells (grade 11) by using a picture of the lead battery to explain electrical phenomena (the generation of an electric current and the recharging of a battery) in terms of the processes at the corpuscular level (i.e., the transfer and transport of electrons and ions). In her report, she described her instructional strategy in steps, providing detailed information about the responses of the students to these steps. Analyzing and reflecting on these experiences, Ann drew conclusions about the usefulness and the limitations of her instructional approach. For instance, the use of the picture of the lead cell had made it possible to reduce the length of her explanations, and to answer students' questions about, for instance, reactions at the electrodes. However, she also concluded that, after her lessons, several students still experienced difficulties in understanding the relationship between the phenomena and the processes at the corpuscular level.

Finally, one PT, Rick, described his struggle with the introduction of the ''mole'' concept to relate amounts of reacting substances to numbers of molecules and atoms. In his report, he described his approach to this introduction, and also discussed his ideas underlying this approach. For instance, he thought about why the mole concept is necessary anyway (in his view, this is because the mass of an atom is too small to handle, whereas chemists need measurable quantities to work with). However, to his surprise, many students had great difficulties understanding the mole, leading him to conclude in his reflective report that to connect the ''world of atoms'' with the ''world of substances,'' where grams and liters are used, ''is just too hard for some students to imagine'' [Rick, reflective report]. He also concluded in his report that, to explain complex topics, it is necessary for him to have a deep and thorough understanding of the content as a basis for thinking about effective teaching strategies. In particular, he formulated the need to use ‘‘convincing examples [. . .] as a bridge between the micro and the macro world’’ [Rick, reflective report]. Thus, he developed teaching intentions that may be seen as the basis of further development of his PCK of instructional strategies.

Conclusions and Discussion

Preservice Teachers' Initial PCK of Using Particle Models

The course module aimed at promoting preservice teachers' PCK of using particle models in teaching chemistry topics. The module emphasized learning from teaching. For that reason, the preservice teachers were not offered research articles about secondary students' learning difficulties and relevant teaching approaches to prepare their lessons, but, instead, they were stimulated to explicate their already existing PCK and to expand this PCK by analyzing and discussing secondary school textbook sections.

Regarding their initial PCK of learning difficulties, the findings show that nearly all preservice teachers remembered having specific learning difficulties, and that, although most of their recollections were fragmented and general, they seemed to be aware of problems associated with understanding the relation between phenomena and corpuscular entities. Their major recollections regarded the difficulties of secondary students in understanding the invisibility of particles, and difficulties students have in relating the properties of substances to the characteristics of the constituent particles. However, the findings also show that their PCK was extended and became more structured after they analyzed and discussed sections of a chemistry textbook. The preservice teachers went beyond the ‘‘anecdotal’’ level of description by suggesting a common explanation for the reported learning difficulties; that is, that secondary students consider corpuscular entities to be the smallest parts of a substance that still have the properties of that substance. This explanatory notion can be considered an important extension of their PCK of learning difficulties.

These textbook analyses and discussions also contributed to the preservice teachers' PCK of useful instructional strategies for overcoming secondary students' learning difficulties. The findings showed that half of the PTs intended to use the strategies that were (implicitly) given in the textbook sections. This preference is not surprising, because, as Yager (1983) has pointed out, (preservice) teachers usually see textbooks as rich sources of information, which have a strong influence on shaping their teaching. In general, the other PTs also intended to follow the textbook, but they would adapt the textbook sections under consideration to prevent possible confusion among students. At this stage of the module, it was of pivotal importance that all PTs acknowledged the potential importance of using models of molecules and atoms to promote students' understanding of the relationships between phenomena, such as the characteristics of substances and processes, and corpuscular entities, such as atoms and molecules.

As a result of the activities in the course module, before teaching, the PTs had become aware of several specific students' learning difficulties, and a possible explanation for such difficulties, as well as some potentially useful teaching approaches with respect to the use of particle models. At the same time, however, the PCK of the individual PTs at this stage of the course module appeared to consist mainly of global and fragmented notions.

The Growth of Preservice Teachers' PCK

Given the design of the course module, it is difficult to make a ‘‘straight’’ comparison of the PCK of the PTs before and after the teaching of their self-designed series of lessons. In particular, the specific topics that were addressed before teaching (i.e., topics which PTs remembered or observed, or topics from the textbook sections) were different from the ones that PTs focused on in their series of lessons. As explained earlier, this was due to the different teaching programs of the PTs in their schools. Nevertheless, from analyses of the data, we concluded that growth of PCK had occurred with respect to the following aspects. First, not surprisingly, referring to experiences concerning teaching their series of lessons, all PTs expressed knowledge of specific learning difficulties, which differed from their knowledge before teaching. Obviously, in most cases, this knowledge was related strongly to the specific topics the PTs had taught. In addition, and more importantly, although their descriptions varied in terms of details and precision, it appeared that the postteaching knowledge of learning difficulties was usually different from that before teaching, in the sense that many PTs went beyond the anecdotal level and analyzed such difficulties in more general terms. For instance, some of them related specific learning difficulties in terms of their students' problems in understanding the abstract nature of particles (cf. John, Joni, and Jim), whereas others drew conclusions about students' views of visible phenomena and invisible particles as two separate "worlds of meaning" (cf. Joe, Wayne, Harry, and Rick). Second, regarding knowledge of instructional strategies, it appeared that about half of the PTs, as a result of experimenting with the use of particle models during their series of lessons, gained a better understanding of the possibilities and the limitations of the use of such models. For instance, some (e.g., Jim, Rick, and Robert) found that the use of particle models, although carefully planned, did not always contribute to students' understanding of the topic under consideration. They presented concrete examples of situations where the use of particle models could be helpful, as well as examples of situations where particle models would be less helpful, or even problematic, for students. Although this was occasionally a disappointing experience, it helped the PTs to formulate new teaching intentions in terms of trying to select examples of useful models (e.g., Robert and Rick).

The findings also showed some notable differences between the PTs. In their lesson reports and during the discussions about these reports, about half of the PTs focused on the students' difficulties they had observed, whereas the other PTs reported mainly on the instructional strategies they developed and used, which, in addition, they related to observed students' difficulties. When these findings are considered more precisely, the sample of PTs can be divided into four subgroups:

- Five PTs reported only on students' learning difficulties (George, Rosie, Joe, Pete, and Wayne).
- Two PTs did the same, but also added new teaching intentions (John and Joni).
- Three PTs reported on instructional strategies which they related to students' learning difficulties (Harry, Jim, and Ann).
- Two PTs did the same, but also added new teaching intentions (Robert and Rick).

In conclusion, through learning from teaching, the preservice teachers further developed their PCK of using particle models, although this development varied from PT to PT. These personal differences may be explained with the help of the recently published Interconnected Model of Teacher Professional Growth (IMTPG; Clarke & Hollingsworth, 2002). This model suggests that teacher learning occurs through mediating processes of reflection and enactment. Through these processes, four so-called domains of teacher learning are connected with each other: the personal domain; the external domain; the domain of practice; and the domain of consequences. In our course module, these domains were incorporated in the design of the constituent parts; for instance, the remembered or observed difficulties ("personal domain"), the textbook analyses ("external domain"), authentic classroom teaching ("domain of practice"), and the teaching intentions (“domain of consequences”). In this model, the development of preservice teachers’ knowledge is seen not as a linear process, but as a complex process that can have different steps and iterations. This process may be influenced by, for instance, the content of a teacher’s personal domain, or by specific experiences in the domain of practice. In the present study, not only was the content of the personal domain different for each PT, but also the domain of practice varied considerably for each participant. Taken together, from the perspective of the IMTPG, it may be expected that these differences led to different processes of reflection and enactment, thus explaining the observed differences in PCK developed by the PTs.

Implications for Teacher Education

The present module was designed to function as an introductory module with respect to learning how to use particle models when teaching chemistry. The teaching of this issue is relevant not only to the specific topics taught by the PTs in the course of this module, but also to many other topics in the chemistry curriculum. As discussed earlier, the module succeeded in contributing to the development of the PCK of the participating PTs, albeit to various extents. Comparing the outcomes of the present study with the previously described guidelines for developing PCK, drawn from the research literature, we can conclude that, generally speaking, these guidelines were useful for the design of our course module. That is, it turned out to be useful to start the module with a series of activities focusing on explicating preservice teachers’ initial knowledge of secondary students’ conceptions and learning difficulties, and expanding these notions by analyzing and discussing fragments from a chemistry textbook. The latter activity also appeared to stimulate their thinking about potentially useful instructional strategies. Next, it was important that preservice teachers were provided with authentic opportunities to experiment with teaching approaches. In this context, some of them appeared to have focused on observing and identifying students’ learning difficulties, whereas others were primarily focused on the design of their instructional approach, and their students’ responses to it. Finally, writing a reflective lesson report, and discussing these reports with each other, turned out to be useful in helping the PTs to explicate, and further develop, their ideas about students’ learning difficulties and instructional strategies—in other words, their PCK.

The data also show that the learning outcomes of the module, in terms of PCK development, were different for different PTs, and mostly limited to the specific issues or topics that were focused on. At the same time, there was also evidence that this introductory module, at least for some PTs, generated needs for further learning—for instance, the need to know how to use visualizations of molecular structures to clarify the relations of these structures with the properties of substances (cf. George and John), and the need to know appropriate examples of particle models (cf. Robert). For this purpose, it would be useful to design a follow-up module with the aim of further promoting preservice teachers’ development of PCK of using particle models. In such a follow-up module, it may be useful to include opportunities to discuss the relevant research literature on secondary students’ difficulties and teaching approaches in the area of particle models. On the basis of their teaching experiences and their explicit needs for learning, we expect the PTs to be able to use the information from this literature in a meaningful way. Again, this institutional activity should be related to teaching in authentic classroom settings, followed by reflection on teaching. Through the use of such an approach, we hope that (preservice) teachers will continue to experiment with teaching approaches, monitor their students’ responses, examine the relevant research literature, and so on, to further develop their PCK as independent learners.

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References

Andersson, B. (1990). Pupils' conceptions of matter and its transformations (age 12–16). In P.L. Lijnse, P. Licht, W. De Vos, & A.J. Waarlo (Eds.), Relating macroscopic phenomena to microscopic particles (pp. 12–35). Utrecht: CDβ-Press.

Baxter, J.A. & Lederman, N.G. (1999). Assessment and measurement of pedagogical content knowledge. In J. Gess-Newsome & N.G. Lederman (Eds.), Examining pedagogical content knowledge (pp. 147–161). Dordrecht: Kluwer Academic.

Bryan, L.A. & Abell, S.K. (1999). Development of pedagogical knowledge in learning to teach elementary science. Journal of Research in Science Teaching, 36, 121–139.

Clarke, D. & Hollingsworth, H. (2002). Elaborating a model of teacher professional growth. Teaching and Teacher Education, 18, 947–967.

Clermont, C.P., Krajcik, J.S., & Borko, H. (1993). The influence of an intensive in-service workshop on pedagogical content knowledge growth among novice chemical demonstrators. Journal of Research in Science Teaching, 30, 21–43.

Cochran, K.F., DeRuiter, J.A., & King, R.A. (1993). Pedagogical content knowledge: An integrative model for teacher preparation. Journal of Teacher Education, 44, 263–272.

De Vos, W. & Verdonk, A.H. (1987). A new road to reactions. Part 4: The substance and its molecules. Journal of Chemical Education, 64, 692–694.

De Vos, W. & Verdonk, A.H. (1996). The particulate nature of matter in science education and in science. Journal of Research in Science Teaching, 33, 657–664.

Erduran, S. (2001). Philosophy of chemistry: An emerging field with implications for chemistry education. Science & Education, 10, 581–593.

Francoeur, E. (1997). The forgotten tool: The design and use of molecular models. Social Studies of Science, 27, 7–40.

Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look to the future. Journal of Chemical Education, 76, 548–554.

Grossman, P.L. (1990). The making of a teacher: Teacher knowledge and teacher education. New York: Teachers College Press.

Harrison, A.J. & Treagust, D.F. (1996). Secondary students' models of atoms and molecules: Implications for teaching chemistry. Science Education, 80, 509–534.

Ingham, A.M. & Gilbert, J.K. (1991). The use of analogue models by students of chemistry at higher education level. International Journal of Science Education, 13, 193–202.

Janesick, V.J. (2000). The choreography of qualitative research design. In N.K. Denzin & Y.S. Lincoln (Eds.), Handbook of qualitative research (2nd ed., pp. 379–399). Thousand Oaks, CA: Sage.

Johnstone, A.H. (1993). The development of chemistry teaching: A changing response to changing demand. Journal of Chemical Education, 70, 701–705.

Justi, R.S. & Gilbert, J.K. (2002). Models and modelling in chemical education. In J.K. Gilbert, O. De Jong, R. Justi, D.F. Treagust, & J.H. Van Driel (Eds.), Chemical education: Towards research-based practice (pp. 47–68). Dordrecht: Kluwer Academic.

Lampert, M. & Loewenberg, D.B. (1998). Teaching, multimedia, and mathematics: Investigations of real practice. New York: Teachers College Press.

Lederman, N.G., Gess-Newsome, J., & Latz, M.S. (1994). The nature and development of preservice science teachers' conceptions of subject matter and pedagogy. Journal of Research in Science Teaching, 31, 129–146.

Loughran, J.J., Milroy, P., Berry, A., Gunstone, R., & Mulhall, P. (2001). Documenting science teachers' pedagogical content knowledge through PaP-eRs. Research in Science Education, 31, 289–307.

Loughran, J.J., Mulhall, P., & Berry, A. (2004). In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. Journal of Research in Science Teaching, 41, 370–391.

Luisi, P.L. & Thomas, R.M. (1990). The pictorial molecular paradigm—pictorial communication in the chemical and biological sciences. Naturwissenschaften, 77, 67–74.

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge. In J. Gess-Newsome & N.G. Lederman (Eds.), Examining pedagogical content knowledge (pp. 95–132). Dordrecht: Kluwer Academic.

Marks, R. (1990). Pedagogical content knowledge: From a mathematical case to a modified conception. Journal of Teacher Education, 41, 3–11.

Morrison, J.A. & Lederman, N.G. (2003). Science teachers' diagnosis and understanding of students' preconceptions. Science Education, 87, 849–867.

Osborne, H.D. (1998). Teacher as knower and learner, reflections on situated knowledge in science teaching. Journal of Research in Science Teaching, 35, 427–439.

Pieren, L., Scheffers-Sap, M., Scholte, H., Vroemen, E., & Davids, W. (1995). Chemie 3HAVO/VWO [Chemistry]. Groningen, The Netherlands: Wolters-Noordhoff.

Sanders, L.R., Borko, H., & Lockard, J.D. (1993). Secondary science teachers' knowledge base when teaching science courses in and out of their area of certification. Journal of Research in Science Teaching, 30, 723–736.

Shulman, L.S. (1987). Knowledge and teaching: Foundations of the new reform. Harvard Educational Review, 57, 1–22.

Smith, D.C. & Neale, D.C. (1989). The construction of subject matter knowledge in primary science teaching. Teaching and Teacher Education, 5, 1–20.

Smith, J.A. (1995). Semi-structured interviewing and qualitative analysis. In J.A. Smith, R. Harré, & L. Van Langenhove (Eds.), Rethinking methods in psychology (pp. 9–26). Thousand Oaks, CA: Sage.

Sprinthall, N.A., Reiman, A.J., & Thies-Sprinthall, L. (1996). Teacher professional development. In J. Sikula, T.J. Buttery, & E. Guyton (Eds.), Handbook of research on teacher education (pp. 666–703). New York: Macmillan.

Tobin, K., Tippins, D.J., & Gallard, A.J. (1994). Research on instructional strategies for teaching science. In D.L. Gabel (Ed.), Handbook of research on science teaching and learning (pp. 45–93). New York: Macmillan.

Van Driel, J.H., Verloop, N., & de Vos, W. (1998). Developing science teachers' pedagogical content knowledge. Journal of Research in Science Teaching, 35, 673–695.

Van Driel, J.H., De Jong, O., & Verloop, N. (2002). The development of preservice chemistry teachers' PCK. Science Education, 86, 572–590.

Yager, R.E. (1983). The importance of terminology in teaching K-12 science. Journal of Research in Science Teaching, 20, 577–588.