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Making PCK Explicit—Capturing Science Teachers' Pedagogical Content Knowledge (PCK) in the Science Classroom

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One way for teachers to develop their professional knowledge, which also focuses on specific science content and the ways students learn, is through being involved in researching their own practice. The aim of this study was to examine how science teachers changed (or not) their professional knowledge of teaching after inquiring into their own teaching in learning studies. The data used in this article consisted of interviews and video-recorded lessons from the six teachers before the project (PCK pre-test) and after the project (PCK post-test), allowing an analysis of if and if then how the teachers changed their teaching practice. Hence, this study responds to the urgent call to focus direct attention on the practice of science teaching. When looking at the individual teachers, it was possible to discern similarities in the ways they have changed their teaching in lesson 2 compared to lesson 1, changes that can be described as: changes in how the object of learning was defined and focused, changes in how the examples that were presented to the students were chosen and changes in how the lessons were structured which in turn influenced the meaning of the concepts that were dealt with. As such, issues for enhancing teachers' professional learning were unpacked in ways that began to demonstrate, and offer insights into, the extent of their PCK development over time.

Keywords: *Learning study; PCK; Pedagogical content knowledge; Teacher knowledge*

Introduction

During the last decades, much of the debate about school improvement concerns the issue of teachers' professional knowledge. In 1986, Shulman conceptualized a

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teacher's professional knowledge (i.e. their own special form of professional understanding) as pedagogical content knowledge (PCK). To further elaborate, PCK is the knowledge formed at the intersection of content and pedagogy that is demonstrated by teachers through their understanding of how particular subject matter or issues are organized, represented, and adapted to the diverse interests and abilities of learners, and then used to engage learners during instruction (Shulman, 1986, 1987). As such, there is no doubt that the teacher plays a key role in the improvement of schools and students' learning outcomes. Therefore, there is a need to address aspects that constitute teacher professional knowledge and how this knowledge can be captured and enhanced by the teachers *themselves* through collaborative inquiry into their teaching and learning (Nilsson, 2014; Vikström, 2014).

One way for teachers to develop their professional learning, which also focuses on specific science content and the ways students learn such content, is through being involved in researching their own practice in a learning study (Kullberg, 2010; Marton & Booth, 1997; Marton & Tsui, 2004; Nilsson, 2014; Runesson, 2006; Vikström, 2008, 2014). This article reports on a research project that aimed to develop science teachers' PCK (Gess-Newsome, 1999; Loughran, Berry, & Mulhall, 2006; Nilsson, 2008, 2014; Nilsson & Loughran, 2012; Shulman, 1986, 1987) through their participation in a learning study. A learning study is a collegial process in which teachers are guided by a specific pedagogical theory, variation theory, and work together with a researcher to explore their own teaching activities to identify what is critical for their students' learning. Another important aspect of the learning study is that it pays attention to how teachers' collective construction of professional knowledge is enacted by making a shift from professional development as something that is done *to* teachers towards considerations of professional *learning* which entails work *with* and *by* teachers (Nilsson, 2014).

During three semesters, two groups of secondary science teachers (three teachers in each group) worked in three learning study cycles (one per semester) together with a researcher in order to create prerequisites and further identify conditions for students' learning of a specific content. In collaboration with a researcher (authors) the teachers conducted three learning studies within the framework of variation theory (Marton & Booth, 1997). In a cyclic process the teachers studied their students' learning in relation to their own teaching while the researcher studied the teachers' learning and knowledge production during the process.

The aim of this study was to examine how the six teachers changed (or not) their professional knowledge of teaching (here referred to as PCK) after inquiring into their own teaching within the three learning studies. The data used in the article consisted of a video-recorded lesson from the four teachers *before* the project (PCK pre-test) and *after* the project (PCK post-test), allowing an analysis of *if* and if then *how* the teachers changed their actual teaching practice. As such, this study responds to the call of Ball, Hill, and Bass (2005) to focus direct attention on the actual practice of teaching (and not on post-teaching reflection which is often used as data to capture PCK). The research question addressed is: In what way does learning study change teachers' PCK?

Although PCK has been one of the most debated conceptions for teacher knowledge, the debate has so far been of very little impact on teacher education and teachers' work (Kind, 2009), and its potential has not been fully realized (Schneider & Plasman, 2011). Further, questions about the nature of PCK for teachers at different phases of their career still remain (Abell, 2007). Therefore, more direct evidence on the extent to which teachers' interaction with peers and researchers enhances changes in classroom practice is strongly needed. This article responds to such a call and builds on two propositions. One is that the way teachers handle and organize the content to be learned is a significant feature of teachers' PCK. Organizing for learning could imply many things such as organizing and arranging the classroom, providing examples and explanations to the students in a conscious way and reflecting carefully on the interactions and the activities in the classroom. However, by organizing for learning with specific content we mean the way the content is sequenced, what connections are made, what relationships are pointed out, what examples are given and how and so forth. Our other proposition is that that teachers can develop this particular knowledge by a process of collaborative inquiry into teaching and learning in their own classrooms with a particular focus on the specific content and how this is perceived by the learners. Both these propositions are dealt with in the article.

PCK as a Way to Conceptualize Teacher Competence

In recent studies (e.g. Hattie, 2009; Heywood & Parker, 2010; Nilsson & Loughran, 2012; Van Driel & Berry, 2012; Vikström, 2014), teacher quality is presented as one of the most important factors contributing to student learning. However, consensus about the exact definition of teacher quality is still a long way off in the field of science education. There is little doubt that the complexity of teaching highlights the need for more extensive research into the relationships between the different elements that constitute teacher knowledge, and how these might support student learning.

The notion of PCK was originally developed by Shulman (1986) to represent one of the professional knowledge bases that an expert teacher possesses, and was later described as representing 'the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented, and adapted to the diverse interests and abilities of learners, and presented for instruction' (Shulman, 1987, p. 8). Hence, PCK has become a way of understanding the complex relationship between pedagogy and content through an integrated process rooted in classroom practice (Van Driel, Verloop, & De Vos, 1998). Ball et al. (2005) stressed that PCK underlies a teacher's development and selection of tasks, the choice of representations and explanations, the facilitation of productive classroom discourse, the interpretation of student responses, the checking of student understanding, and the swift and correct analysis of student errors and difficulties. Schneider and Plasman (2011) noted that PCK is a heuristic for teacher knowledge that can be helpful in untangling the complexities of what teachers know about teaching and how it changes over broad spans of time. With these definitions in mind, we conclude that

for educational researchers, PCK has been a seductive notion that has drawn many to explore how it might be better recognized and developed.

As PCK is deeply rooted in a teacher's everyday work it is reasonable to suggest that it encompasses both theoretical dimensions and experiences gained from ongoing teaching activities. One interesting tension in the perception of PCK with consequences for teachers' professional development is the following: On the one hand it is a *static knowledge*, something that teachers know about teaching in a way that promotes students' understanding; on the other hand it is *dynamic knowing* or a skill that teachers process in the classroom. This distinction was emphasized by Van Driel et al. (1998) who used the concept craft knowledge in order to refer to 'the knowledge teachers have with respect to their teaching practice' (p. 674). The dynamic nature of PCK was also emphasized by Magnusson, Krajcik, and Borko (1999) who stated that the 'development of PCK is not a straightforward matter of having knowledge; it is also an intentional act in which teachers choose to reconstruct their understanding to fit a situation' (p. 111).

Cochran, DeRuiter, and King (1993) proposed the term pedagogical content knowing (PCKg), which is defined as 'a teacher's integrated understanding of four components: pedagogy, subject matter content, student characteristics, and the environmental context of teaching' (p. 266). Integration is the key functional term that underlies pedagogical content knowing; pointing out that all four of its components must be learned and applied simultaneously, but not necessarily in equal parts in every learning experience. Cochran et al. (1993) strongly argue that pedagogical content knowing is best learned while working directly with school students because 'live teaching permits the direct interaction that shows ideas in use and opens the way to negotiating paths of understanding' (p. 267). With these ideas in mind we suggest that PCK is basically rooted in actual classroom practice and can only be analysed during teaching. Therefore, capturing teachers' PCK in the *act of teaching* particular content to a specific group of students might be one way to gain insight into those factors that make a difference for students' learning of science.

Variation Theory as a Way to Capture Teachers' PCK

Variation theory (Lo, 2012; Marton & Booth, 1997; Marton & Pang, 2006; Marton & Tsui, 2004; Runesson, 2006; Vikström, 2008) represents a theoretical framework that can guide teachers in their practice to provide students with necessary learning opportunities. The theory postulates that learning is always directed at 'something' and that it is related to how people understand this 'something'. For example, if we want students to understand the concepts from chemistry and make relevant use of them, we must ask, 'What does it take for the students to gain the knowledge we require?' The primary contribution of the theory is that it directs the focus towards the 'object of learning'. The focus is then not only upon the logic of the subject matter itself, but also upon the logic of the students, that is, the various ways the students experience the content to be learnt. It can therefore be used as a tool to understand some of the necessary conditions for learning and to help teachers make wise decisions

when teaching (Ling & Marton, 2012; Lo, 2012; Marton, 2014; Marton & Pang, 2006).

With its particular focus on the content to be learnt, variation theory has much in common with established teaching principles and with teachers' use of PCK. Teachers have to take into consideration the knowledge and understanding that students bring with them (knowledge of students' understanding); they must know subject matter in depth (knowledge of content); and metacognitive skills must be integrated. Shulman (1986) noted the importance for teachers to use the content to build on and to provide examples in order to promote students' understanding. Traditionally, teachers often give a lot of examples of the same concept in order to promote a general understanding. What variation theory tells us, however, is the importance to focus on how examples and explanations are provided to the students in terms of focusing on differences and similarities between concepts instead of the concepts alone. Pang and Marton (2013) emphasized that learning is a function of discernment, and discernment is a function of variation. We can become aware of a feature by experiencing a contrast, as in contrasting matter (with mass) with energy (without mass). That contrast, provided that we experience the two concepts at the same time, may help us realize that sunlight and heat have no mass. Taylor and Rohrer (2010) indicated that contrasting concepts and providing instructions with intermixed examples promote better learning outcomes on post-instruction tests compared to instruction where one thing is presented at a time. In terms of a teachers' PCK, these issues are important for how content is planned and taught in a way that most successfully promotes student learning.

PCK is characterized by two key components: knowledge of representations of subject matter and understanding of specific learning difficulties and student conceptions. These components underlie teachers' instructional decision-making both during the planning stage of the lesson—through decisions of how to best present content to students—and during classroom instruction through interaction with students in order to make the content understandable. According to variation theory, discernment of critical aspects is a prerequisite for learning and variation a prerequisite for discernment (Marton, 2014). As such, a teacher must be able to conduct certain patterns of variation when teaching. Throughout a learning study, and with the object of learning as a point of departure, variation is applied in three ways (Lo, 2012; Pang & Ling, 2012):

(1) Variation of students' ways of understanding the object of learning.
(2) Variation of teachers' understanding and ways of dealing with the object of learning.
(3) Variation as a guiding principle for pedagogical design; identifying critical aspects and creating patterns of variation in a systematic way to enable students to discern those aspects of the subject matter.

Recently, a number of studies have been published that concern variation theory and learning studies as tools for promoting teachers' professional learning. Nilsson (2014)

and Vikström (2014) indicated how variation theory was a useful guiding principle when teachers were engaged in pedagogical design, analysis of lessons and evaluation of students learning, as well as a valuable tool for adapting research results into practice. Pang and Ling (2012) demonstrated the power of variation theory for teachers' learning when explaining and predicting the relationship between the teaching and the students' learning. Tan and Nashon (2013) captured three aspects of the participating teachers' learning: (1) increased degrees of student-centred pedagogy and challenges to teachers' prior assumptions about science pedagogy, (2) increased awareness of possibilities and limitations of their beliefs about science pedagogy and (3) emergence of new understanding about curricular content and science pedagogy. Elliot's (2013) evaluation of learning studies in Hong Kong also supports the view that teachers' professional development was enhanced by variation theory. Aspects of PCK of the two groups of science teachers in this particular study have also been described in earlier publications (Nilsson, 2014; Vikström, 2014). All these studies provide important evidence that variation theory and learning studies are successful tools for developing teachers' professional knowledge.

Learning Study as a Methodology to Develop Teachers' PCK

In a learning study, the conditions for students' learning are identified and reflected upon. Such awareness is important in terms of PCK as it focuses on the relation between the content, the teaching and students' learning. A learning study is a cyclical process (see Figure 1) in which teachers reflect on necessary conditions for learning a specific content and how to meet these conditions in the learning situation.

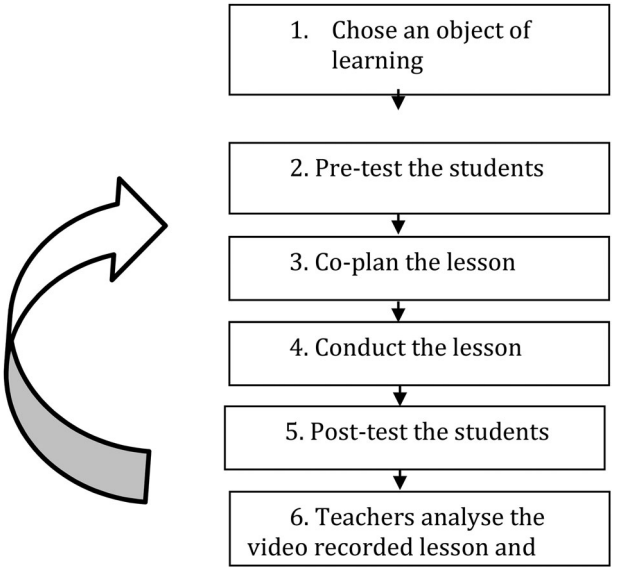

Figure 1. Steps in the learning study cycle

Kullberg (2010) describes that the goal of a learning study is to enhance student learning and explore what it takes to learn something particularly. In the learning study the teachers explore their teaching to identify what can be critical features for their students' learning.

> The notion of critical features is used to describe features with regard to the content and students' understanding of what is taught, what it is necessary to be aware of to be able to experience what is to be learned in a certain way. (Kullberg, 2010, p. 18)

A learning study starts with the teachers (normally a group of three teachers) who identify an object of learning, often something normally experienced as being problematic for students to learn about. Then, the students' prior knowledge and their existing perceptions are investigated, typically with a pre-test. The teachers, together with the researcher, analyse the test results to provide an insight into how students experience what is to be learned and that which is critical in order to learn the specific object. The variation in how students experience what is to be learned then becomes a source of planning the first lesson. One teacher conducts the lesson (lesson 1), which is video-recorded. After the lesson the students are given a post-test in order to provide insight into how the students' understanding of the object of learning and its critical features is changed (or not) after the instruction. The teachers and the researcher collaboratively analyse the video-recorded lesson (lesson 1) together with the students' pre- and post-test results in a stimulated recall session (Calderhead, 1981) in order to share their experiences of the lesson with a focus on evidence of student learning and analysis of the teacher's instruction. As such, the purpose of the stimulated recall session is to capture aspects within the lesson that makes difference for students' learning and to revise it.

Then, in the next phase of the learning study the second teacher conducts the (revised) lesson with his/her class (lesson 2) and the same procedure follows, with analysis of the lesson and the pre- and post-test results. Finally, the third teacher conducts the (again revised) lesson with his/her class following the same procedure. As such, the learning study is an iterative process of planning, analysing and revising a lesson (on a specific object of learning) with the aim to improve both students' and teachers' learning.

Throughout the process, different qualities of the lesson are analysed through critical questions concerning what is to be learnt, why and how, and how is students' learning captured. After the lessons, when the video recordings are analysed in relation to the results of the post-tests, patterns of variation that improved students' learning are to be identified.

Participating in a learning study can be challenging as teachers must develop enough trust to share tensions and dilemmas of personal practice involving participants to speak honestly and personally when unravelling the complexity of teaching. Adamson and Walker (2011) noted this challenge and highlighted that a learning study is fraught 'with potential tensions, such as outsider versus insider perspectives; academic versus grounded knowledge bases; unclear hierarchical statuses;

and diverse and conflicting agenda' (p. 35). With these challenges in mind, this article values the knowledge generated by six secondary science teachers from their experiences of collaboration and structured reflection on their own and their students' learning as a way to bring together reflective and dialogic processes of professional learning.

Data Collection and Analysis

During three semesters, six secondary science teachers (in two groups) participated in three learning study cycles each (one per semester) together with a researcher (authors). The data used in the article consist of individual interviews and a video-recorded lesson from the teachers *before* the learning studies (PCK pre-test) and *after* the learning studies (PCK post-test), allowing an analysis of *if* and if then *how* the teachers changed their teaching practice.

All teachers were experienced science teachers, had worked together for several years and had volunteered to participate in the project. All the participating students had written consent from their parents.

Before initiating the project, all teachers were informed that the project was built around the idea to analyse how the teachers developed their teaching over time. Therefore, data from a lesson about one particular topic should be collected before and after the learning study cycles. The teachers were told to be free to choose both the content and the way to teach the content. An important issue was that both lessons (PCK pre-test and post-test) should include the *same* content. In contrast to the lessons in the learning studies, the teachers planned the lessons on their own, without influence from their colleagues or the researcher (Figure 2).

Capturing PCK requires a combination of approaches that can collect information about what teachers know, what they believe, what they do and the reasons for their actions (Baxter & Lederman, 1999). Therefore, in this study we used different ways to collect data. (1) In the interview before the PCK test-lessons, the teachers were interviewed about their overall intentions for their lesson, what they wanted their students to learn, what instructional strategies they intended to use and for what reason,

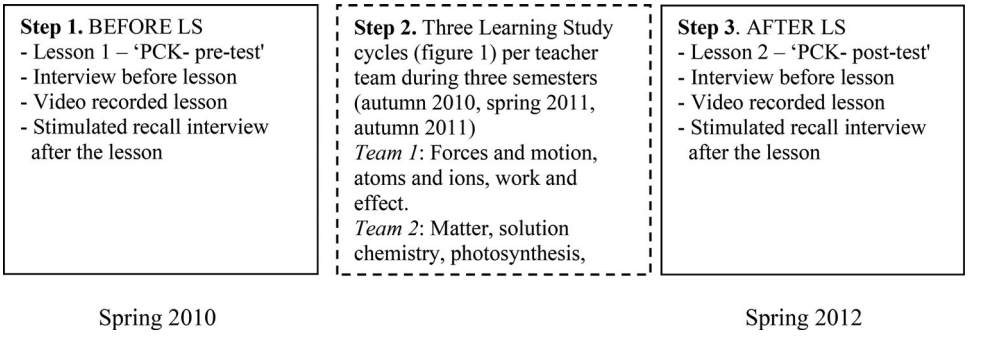

Figure 2. Design of the study. The lessons in 1 and 3 were individually planned and were about the same topic for the same teacher, but different between the teachers

what they knew about the students' prior knowledge and learning difficulties and what they considered difficult for their students to learn concerning the specific content. (2) The lessons were then video-recorded by the researcher with a focus on the teachers' enactment of science teaching. The lessons lasted for about 40–50 minutes. (3) A few days after the lesson the teacher was interviewed once again, this time in a stimulated recall interview. In this interview the researcher and the teacher discussed the lesson together to provide information of the teachers' awareness of the connection between the intended and enacted object of learning and the learning possibilities that were offered to the students. The interviews before and after the video-recorded lesson were tape-recorded and transcribed in verbatim.

The video-recorded lessons in the PCK-tests offered possibilities to analyse the process in the classroom (Jordan & Henderson, 1995). The video recordings were transcribed as a detailed description of what happened during the lesson from the beginning to the end. Variation theory was used in the analysis, meaning that the researchers looked for patterns of variation (Marton, 2014) that made it possible for the students to discern aspects and understand the content in specific ways.

Data analysis involved two steps. First, and most importantly, the video-recorded PCK test-lessons were analysed by both researchers individually with a sharp focus on how the teachers enacted the specific content in the lesson and how their teaching changed (or not) between the two lessons. Second, the transcribed tape recordings were analysed through content analysis (applied in the way described by Miles & Huberman, 1994) in order to identify changes in the teachers' ways of reflecting on their teaching. A content analysis of this kind is based on the view that it facilitates the production of core constructs from textual data (e.g. a systematic method of data reduction, data display, and conclusion drawing and verification).

The analysis began on a general level with the verbatim transcriptions of the interviews and video recordings by repeatedly reading them as a whole and by getting to know them as a collective—following a typical variation theory approach to data analysis (Marton, 2014). The analysis then continued with a focus on systematic identification of parts of the transcripts, enabling a transformation into a set of units that made it possible to organize the differences between lessons 1 and 2 in a thematic way.

Variation theory was used throughout the analysis, meaning that an overall question was 'What critical aspects are made possible to discern through the actions and interactions that are enacted in the lesson?' Codes that were used in the analysis were observed for differences in: organization of content, what examples were given during the lessons, how the examples were structured, what was written on the whiteboard and how the dialogue and interaction during the lessons with the students influenced the learning possibilities. The differences in the enactments of the lessons were then compared to how the teachers expressed their intentions with the lessons, what they had said about their students' learning difficulties, and how they reflected upon their own teaching in relation to and the learning possibilities that were offered.

When analysing how the content was organized, several aspects were considered: What components of the content were present in both lessons 1 and 2 and what was not? How much time and attention were spent at each component? Each example

given by the teacher, orally or written on the whiteboard, was taken into account. What examples were given? In what order and in what way were they presented to the students? In what aspects are the teacher's ways of enacting the lesson connected to the teacher's intentions and reflections about his/her teaching and to the students' learning as expressed in the interviews? What are the differences between lessons 1 and 2 according to the intended and enacted object of learning?

Finally, when that kind of detailed differences between the lessons were revealed, two more general questions were asked: First, what traces of the teachers' experiences from the learning studies are to be captured? Second, if a teachers' professional object is defined as to bring about learning of specific objects of learning, what can then be said about the teachers' development of PCK through their participation in the learning studies? In this way, the primary mode of analysis was the development of categories from data into a framework that captured the key themes of how the teachers developed aspects of their PCK. In order to guarantee the validity of coding, the analysis was first made by the two authors separately; then the two researchers met to discuss and refine the categories until a consensus was reached.

Park, Jang, Chen, and Jung (2011) demonstrated the possibility of reliably measuring particular aspects of PCK to estimate the whole construct. In this article, the analysis focuses on '… the intentional act in which teachers choose to reconstruct their understanding to fit a situation' (Magnusson et al., 1999, p. 111), an act in which different PCK components interact in a dynamic way. This way of approaching PCK supports the call of Friedrichsen, Driel, and Abell (2011) to investigate PCK from different perspectives, instead of categorizing teachers into only one of the categories of Magnusson et al. (1999) or any other list of categories. As such, the teachers' development of PCK during the project is captured through an investigation of how the teachers developed their ways of teaching a specific content to enhance students' possibilities to grasp the object of learning, and further, how this knowledge was manifested in their teaching actions.

Results—Changes in the Teachers' Ways of Handling the Content

Four of the six teachers demonstrated evident differences in how they handled the content in lesson 1 compared to lesson 2. As one of the teachers performed the lessons more or less in the same way, and another teacher did not teach the same topic in lesson 2 as in lesson 1, these two teachers were excluded in the examples below.

The teachers' developed PCK is presented in a way that makes explicit (1) components of PCK (e.g. to make critical aspects within the teaching practice visible); (2) how these components are observed within subsets of the lessons (e.g. through patterns of variation, contrasts in the lesson); (3) changes (differences between lessons 1 and 2 in terms of learning possibilities through patterns of variation and (4) teachers' learning from the learning studies (e.g. the teachers' experiences). The result, in terms of how the teachers changed their ways of handling the content between lesson 1 (in 2010) and lesson 2 (in 2012), will first be described on an individual level and then, in the Discussion section, discussed at a collective level.

Ann

Ann's lessons were about connecting diodes into electrical circuits as a preparation for an upcoming practical task. She expressed her intentions in a similar way in both lessons 1 and 2: she wanted her students to understand that the current can only pass through the diode in one direction and that this was important to understand when connecting diodes into complex circuits. In lesson 1, lots of unnecessary information about electrical components (the resistor, the potentiometer, the thermistor and the photo resistor), none of them of any importance for the upcoming task, were presented and the diode became one component among others. All the components were presented one at a time and in the same way; the component's name, its symbol in circuit diagrams and how it could be used were dealt with. Ann lectured and made short notes on the whiteboard. As such, it might be argued that the main purpose of the lesson, to connect the diode, was not made explicit.

In lesson 2, on the other hand, the diode and how to connect it was the clear focus. Ann chose to present only the diode and several examples of how it could be connected to lamps and batteries, both in series and in parallel. She provided her students with equipment that was used to make different kinds of electric circuits, all of them meant to give the students a variety of experiences related to how the diode could be connected to lamps and batteries. Her students were instructed to connect the diode in series and in parallel in order to highlight different ways to light the lamps. She also deliberately urged the students to connect the diode in both the wrong and the right ways to show how this influenced the lamps. This activity made the students focus on something Ann knew was a common difficulty, namely to connect the diode in the right direction relative to the direction of the current. For every example of connections (also the wrong ones), Ann drew a corresponding circuit diagram and made notes on the whiteboard. In the interview after lesson 2, Ann emphasized:

> Ann: I explain in a different way now. I focus on the components that are important, how to connect the diode in parallel in a way that should have an effect on all lamps. I know that this has been a problem for the students, as well as putting it in the right direction. Now they could see for themselves what happened if they put it the wrong way. And they didn't ask for help as much as they used to do when they constructed the door signal this time. I believe I do such things quite often now, without thinking, creating contrasts like 'light—no light'.

In the interviews before both her lessons, Ann expressed that the students should learn how to connect the diode correctly. But the core idea of Ann's intentions was much more focused in lesson 2 than in lesson 1 and the two lessons offered her students very different possibilities to understand how to connect the diode. Even if she told her students how, and why, it was important to connect the diode the correct way in the first lesson, the meaning of the 'correct way' was not as obvious as in lesson 2. In the second lesson, several alternatives of connections were tested, and 'right ways' were pointed out by contrasting them to 'wrong ways'. Ann's intentions then became more in line with how she enacted the lesson. The differences between Ann's lessons showed clear evidence of how her participation in the learning studies

had influenced her teaching. Contrasting right and wrong ways of connecting the diode is a typical example of an application of variation theory and even if she was well aware of her objectives and students' learning difficulties already in lesson 1, the learning possibilities in lesson 2 were much more obvious according to her aims with the lesson. Her awareness of contrasting concepts as a way to promote students' understanding was expressed in the final interview:

> I have noticed that I use variation quite naturally now when I am teaching. When I give an example of something, I often give another example of what that something is not at the same time, to create contrasts.

Kay

Kay expressed her intentions before lesson 1 in quite a vague manner. The lesson was about acids and bases and she wanted her students to 'recognize an acid' and to 'know something about the pH-scale'. She also expressed her students' learning difficulties as 'to understand this thing about the ions is always difficult'. The major part of Kay's first lesson was used to experiment and talk about acids at a macro level. For example she illustrated the concept 'acidic' by discussing the sour taste of acids and by demonstrating the colours of different indicators together with different acids. The concept 'basic' was more briefly illustrated with the indicator Bromthymol (BTB). The micro level was just shortly exemplified when Kay talked about hydrogen ions, but the hydroxide ion and the water molecule and how the ions were connected to each other and the pH-scale were not mentioned at all. At the end of the lesson she demonstrated the pH-scale briefly and tried to explain its logarithmic function. To illustrate the way Kate provided examples and explanations to the students during the two lessons, Figure 3 illustrates Kay's whiteboard at the end of the first lesson. Examples related to the concept acids and acidic were focused at the beginning of the lesson while the concept neutral, bases and basic was dealt with at the end of the lesson but far more briefly.

In lesson 2 Kay defined her object of learning more precisely.

> Kay: I want them to see the differences between acids and bases as two opposite characteristics that can neutralize each other and that pH is a question of excess or loss of hydrogen ions.

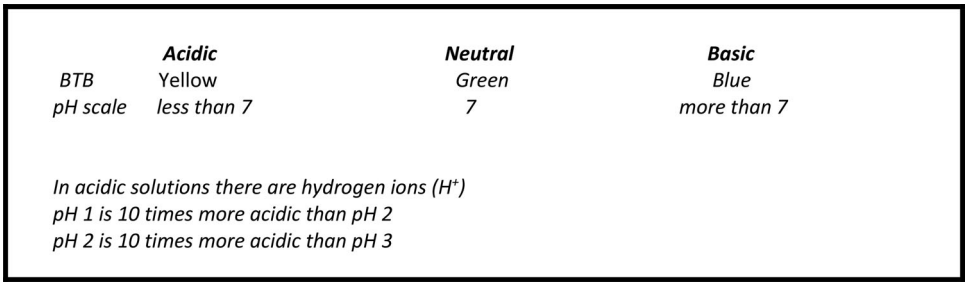

Figure 3. Kay's whiteboard after lesson 1

Kay talked simultaneously about acids and bases, starting at a macro level and ending at a micro level. Her notes on the whiteboard (Figure 4) followed the same structure, both horizontally and vertically. This strategy made it possible to see the contrasts between the concepts and how they were connected to each other. Kay spent less time at the macro level and focused on the micro level, 'I don't avoid the micro level as much as I did before, I think I have been afraid that they shouldn't understand'. Her examples pointed out the connections between the water molecule, the hydrogen ion, the hydroxide ion and the pH-scale and how this could be related to the concepts 'acidic' and 'basic'.

What does it mean to 'recognize an acid' and what is the meaning of 'being acidic'? Even if these issues are dealt with in both of Kay's lessons, the object of learning that was manifested in the lessons became different. In the first lesson, an acid became something that is yellow together with BTB and has a sour taste while the micro level remained unclear. In the second lesson on the other hand, colours and taste are mentioned but are not central. Instead, the concepts 'acid and acidic' provided their meaning by contrasting them with 'base and basic'. This is consequently done throughout the whole lesson, from the initial experiments and dialogue about characteristics at the macro level to all the examples at the micro level. An 'acid' then became the opposite of a 'base' and 'acidic' and 'basic' as well as the pH value something that depended on the amount of hydrogen ions. It also became clearer how the hydrogen ion and the hydroxide ion are connected to each other, to the water molecule and to the concept of neutralization.

Kay's experiences from the learning studies were clearly manifested in lesson 2. Variation theory seems to have guided her to treat the concepts related to acids and bases simultaneously and also provided her with tools that might help her students to overcome the learning difficulties she was well aware of.

Mark

Mark expressed his intentions with lesson 1 as to make the students understand the atom model, mixtures and chemical compounds. In the lesson he began by asking a student to draw a model of an atom on the whiteboard, then continued with neutrons,

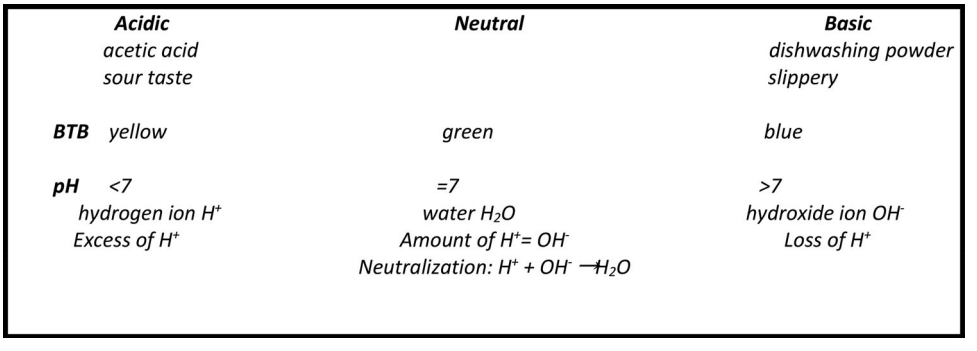

Figure 4. Kay's whiteboard after lesson 2

protons, electrons, how different elements can have different isotopes, the periodic table, photosynthesis and cellular respiration. He worked his way through different concepts one by one until he finally ended up with 'chemical compound'. In the lesson, Mark was very attentive to students' ideas and previous conceptions and in order to increase students' interest he tried to connect to their ideas as much as possible, without any predestinated plan. He went from micro to macro providing one example after another. However, in his attempt to use a lot of different examples, he lost the connection to the intended object of learning. For example he discussed different elements and how to recognize the different elements only through looking at the periodic table without really relating to the atom model, mixtures and chemical compounds with the students. In his interaction with the students he put a lot of effort into building on students' earlier experiences. As such, his endeavour in lesson 1 to catch students' ideas and conceptions sometimes lead him away from the actual object for learning.

In lesson 2, Mark changed the object of learning from the atom model, mixtures and chemical compounds to the 'difference between an atom and an ion'. Even though this object of learning is slightly different from that in lesson 1, his focus remained on the atom. However, in lesson 2 the focus was not only on the two concepts alone but how the concepts were similar and different from each other. Compared to lesson 1, he now puts a stronger emphasis on illustrating how the concepts are related to each other and to their differences and similarities, something that the variation theory postulates as a guiding principle.

> Mark: It is the difference we are going to focus on, the difference between an atom and an ion. And as we just heard, the difference is connected to the charge. As you see there is a connection between the charge and the way the atom is built and what we are going to do today is to take a closer look at these differences and similarities.

Mark's examples were now more focused towards the intended object of learning and instead of only giving the students a large number of examples he uses examples and tasks which put the emphasis on the *differences* instead of on the concepts alone. He used a task with pictures of models of atoms and ions and the students should decide if the model illustrated an atom or an ion. In his second lesson, Mark managed to provide examples that were more focused with fewer concepts involved. His strategy in lesson 1 (i.e. to use a variation of explanations) was now changed into a strategy where variation was used as *a way to focus*. On the whiteboard, he drew an atom and an ion and highlighted the differences and similarities in order to make the students understand them both. Further, when he chose examples in his second lesson he built on his previous experiences of students' previous knowledge and misconceptions that also made him use examples to clarify how electrons move around the nucleus and further, how electrons can move from one energy level to another.

In lesson 2, Mark highlighted critical aspects such as that the atom is made of protons, neutrons and electrons and that in an atom the number of electrons is always the same as the number of protons.

> Mark: I don't want to include too many things at the same time. The difficulties for the students are that they need to focus on so many different concepts at the same time so they mix them all up. Because it is not very much that separates an atom from an ion so they should actually manage to catch it quite easy … .

He systematically dealt with these critical aspects and strove to contrast them towards each other. In this way, he uses his knowledge of students to reconsider his lesson to better meet students' learning needs.

Amy

Amy expressed her intentions before lesson 1: to give an overview of several important topics but also to make the students understand the concept of pressure and let the students discuss what pressure is. She did not clearly define the object of learning more than that she wanted the students to 'understand about pressure'. In the interview before lesson 1 Amy noted:

> Amy: I am going to talk about why water boils at different temperatures depending on where you are on the earth. I will also talk about different liquids and gases and their different pressure and how we use pressure in our everyday life in water towers and when we walk on snow. I also want to talk about what is important to know when you fall into an ice hole and make connections to their everyday life and why it is important to understand what happens around them.

In her first lesson, Amy used several examples, one by one, in order to explain air pressure and to help the students see the relation between the area (surface) and the pressure. She provided examples such as walking and skiing, etc. She also discussed how to rescue a person that has fallen into an ice-hole and tried, through different examples to connect that to force, surface and pressure. Amy also illustrated an example of Archimedes principle. She highlighted the different concepts one by one without any contrasting between them. It is evident that Amy attempted to introduce too many concepts related to pressure in lesson 1 without really defining the pressure alone. As she talked about pressure in air and liquids and gave examples of these concepts, the students became confused and she lost her focus on the object of learning. In her second lesson, Amy's intentions were to teach the difference between force and pressure.

> Amy: I did this two years ago but then my main focus was only on pressure. But when I had this lesson last time I noticed that the students mixed 'Force' and 'Pressure' and did not really understand the difference between them both. My intention this time will be to focus on contrasting these both concepts.

When choosing her examples in lesson 2 she was far more focused, relying on earlier experiences. For example, just to show the relation between force and pressure she explained the definition of force she uses a football and contrasted three different ways of how force could act on the ball. She put the ball on a table to discuss the forces, she kicked the ball and finally she pressed her hand against the ball, both with one finger and then with her whole hand. By doing this, Amy actively integrated

her knowledge of subject matter; science curriculum (i.e. the difference and relations between force and pressure) and students' misconceptions associated with these ideas, and then applied the resulting PCK to the students through instructional strategies such as questioning and discussion.

In her second lesson, Amy also had a clear focus on the object of learning and she highlighted the difference between the concepts and how the concepts were related instead of taking the concepts one by one. The question of *what does it mean to understand pressure* was integrated in her actions and she used several different examples to contrast the relation between force (and its relation to mass and gravity), surface (area) and pressure. She also, in a much more focused way, built on her own experience from earlier lessons about what students' experience as difficult. Even if both Amy's lessons dealt with the concept of 'pressure' Amy managed to define and manifest the object of learning differently in lesson 2 than in lesson 1. The concepts included in the lesson 2 were reduced and the *intended* object was more in line with the *enacted* object of learning.

Discussion—Changes in Teachers' Pedagogical Content Knowing

This study pays attention to how teachers handle and organize the content in order to promote students' learning. Shulman (1987) noted that developing PCK involves a considerable shift in teachers' understanding

> from being able to comprehend subject matter for themselves, to becoming able to elucidate subject matter in new ways, reorganize and partition it, clothe it in activities and emotions, in metaphors and exercises, and in examples and demonstrations, so that it can be grasped by students. (p. 13)

As such, teachers' professional knowledge can be defined as a teacher's ability to make learning possible for students.

Through their collaboration in the three learning studies the teachers learned about the relationship between what was intended, what was enacted and what was learned. The teachers' learning in the learning studies was reflected in their ways of handling the object of learning in the PCK post-test but also in the way they talked about their teaching in the interviews after the learning studies. Nuthall (2004) noted that teachers need to acquire a theory that can be used as an explanatory model and as a guiding principle for understanding the relation between their teaching and their students learning. The theory should also lead the teacher to more easily understand what to look for and how to interpret his or her teaching (Nuthall, 2004).

> Only when teachers understand the principles by which their actions shape the learning process going on in the minds of their students will they be able to ensure effective learning regardless of the abilities or cultural backgrounds of the students. (p. 301)

Finding a balance between the perspectives of theory and practice is important so that the construction of knowledge can be a valued driver to educational change. We suggest that the particular use of variation theory as a guiding principle in their

teaching, as well as their participation in the three learning study cycles made the teachers (re)consider their science teaching in a way that indicates a development of PCK.

In this article, our focus has been to identify *changes* in the teachers' teaching practice before and after their participation in a learning study project. During the three learning studies, earlier research (Nilsson, 2014) indicates that the teachers developed knowledge of how student thinking was impacted by particular instructional strategies through interpretation and collegial analysis of student responses in relation to inferences about these strategies. Even though the data in this particular study are built around individual teaching (PCK pre-test and PCK post-test), we conclude that through their reflections, the teachers realized the need for expansion or modification of their planning or teaching the particular topics, and as such, developed their knowledge-in-action. Consequently they made additions to, reorganized or modified their existing body of PCK for teaching the different topics. Cochran and her colleagues (1993) emphasized the direct interaction between teachers and students in the classroom that shows ideas in use and opens the way to negotiating paths of understanding.

The individual cases indicate how the teachers actively changed their teaching of the specific content in a way that provided new possibilities for students to grasp the object of learning. The four teachers in the project expressed changes concerned with both the ways in which they managed to identify the object for learning and their approaches to teaching this specific content and the underpinning reasons for that approach (i.e. the special amalgam of content knowledge and knowledge of general pedagogy that is the foundation of PCK). As such, issues for enhancing teachers' professional learning were unpacked in ways that began to demonstrate, and offer insights into, the extent of their PCK development over time. In this discussion we will briefly discuss three overarching and inter-related themes and their relations to earlier research on teachers' PCK.

Changes in How the Object of Learning was Defined and Focused

In comparing lesson 1 with lesson 2 it was evident how all four teachers' intentions became more clearly expressed and the content more limited in the second lesson compared to the first (e.g. Kay's way of focusing acid and bases as two opposite characteristics). As a consequence, the intended object of learning was more in line with the enacted object of learning. In lesson 2, connecting the diode correctly and recognizing the differences and connections between acids and bases, atoms and ions and force and pressure were focused. As such, a key insight for all teachers was to limit the learning object, and thus discern the science 'Big Idea' (Loughran et al., 2006; Nilsson & Loughran, 2012), and develop an increased knowledge about the relationship between subject content, teaching and student learning, in other words, those aspects that are central to a teachers' PCK. The teachers' ways of identifying and focusing on that which was to be learnt also refers to the PCK component knowledge of science curriculum described by Park and Oliver (2008) as a knowledge that 'enables teachers to

identify core concepts, modify activities, and eliminate aspects judged to be peripheral to the targeted conceptual understandings' (p. 266).

Changes in How the Examples that were Presented to the Students were Chosen

All four teachers changed the way they presented the examples (e.g. focusing on differences and similarities between concepts instead of only the concepts alone) to better meet their students' learning needs. Ann highlighted right and wrong ways to connect the diode, Kay how the hydrogen ion and hydroxide ion were connected to the water molecule, Mark pointed out how the electrons made the difference between atoms and ions and Amy put her effort on exemplifying and illustrating the relation between pressure, surface and force. As such, the four teachers placed a great emphasis on students' understanding of the specific content in both their planning and enacting of the lessons. All examples provide evidence of how the teachers developed their way of 'reconstructing their understanding to fit a situation' (Magnusson et al., 1999, p. 111) and PCK as a consequence. Evidence is also provided by examples of how the teachers were guided by variation theory as a result of their participation in the learning studies. By using conscious contrasts instead of presenting irrelevant examples, the examples that were chosen highlighted students' learning difficulties and the critical aspects of the object of learning. As such, it is reasonable to suggest that their planning and enacting of teaching a particular topic to confront student misconceptions and to meet their learning difficulties indicated a change in their knowledge of students' understanding and knowledge of instructional strategies (Magnusson et al., 1999).

Changes in How the Lessons were Structured which in Turn Influenced the Meaning of the Concepts that were Dealt with

A clear focus and awareness of what the students should understand instead of more vague ideas of the goal of the lesson, made it possible to give the different concepts that were brought up in the lessons a new meaning. Atoms get their meaning when being contrasted to ions, acids get a new tenor when being contrasted to bases, pressure get new meaning when being contrasted to force and what it means to connect the diode in the right way becomes clearer by contrasting it to the wrong ways. Teachers' knowledge of students' understanding in science and knowledge of instructional strategies is suggested as critical in shaping the structure of teachers' PCK (Park et al., 2011). In terms of how the teachers restructured their lessons in order to provide the students with possibilities to better discern the critical aspects, might also indicate that PCK development had occurred as a result of reflection related to both 'knowledge-in-action' and 'knowledge-on-action' (Park & Oliver, 2008) in the learning studies.

Cochran et al. (1993) defined PCK as the way in which teachers relate their pedagogical knowledge to their subject matter knowledge in the school context. As Park et al. (2011) suggested, providing teachers with opportunities to analyse students' understanding of science and come up with teaching strategies to meet their learning

difficulties are important aspects of teachers' PCK. The result presented in this study supports the idea that teachers do not simply receive knowledge that others create to teach, but produce knowledge for teaching through their own experiences. With its focus on collegial planning and reflection through the learning study design, this study also corresponds with the ideas of Van Driel and Berry (2012) who highlighted the importance of 'forms of professional development for teachers that are built on collaboration, collegial interaction and the fostering of relationships' (p. 26). Therefore, learning study can be described as both a research method and a successful model for continuous professional learning of teachers.

Why Describe Science Teachers' Ways of Teaching a Specific Content in Terms of PCK?

Variation theory emphasizes how the content can be handled in powerful ways, a defining quality of the teaching profession. The object of learning has to do with the capabilities the students are expected to develop, and what they therefore need to learn. According to variation theory the aspects of the object of learning that are discerned and focused on simultaneously define the way in which it is seen. From this follows that the teacher must make it possible for students to discern the aspects that are found critical for a certain object of learning.

What happens in the classroom should ideally reflect the intended object of learning. This can be done by pointing out and explaining patterns and relations that bringing about the enacted object of learning. There are thus two closely related core components of teachers' professional competence (Marton, 2014):

(1) The teacher ought to have insights into the different ways that students see and handle (and should become able to see and handle) the various objects of learning. This component refers to the identification of critical aspects.
(2) The teachers ought to have insights in what way they might handle those objects of learning in order to enable the students to handle them in ways that are as powerful as possible. This component refers to the constitution of patterns of variation.

Marton (2014) noted that

> … you cannot have pedagogical content knowledge without content knowledge: you can only have insights into the students' ways of handling the content of an object of learning in relation to your own way(s) of handling that content, and you can only contribute to enabling the students to handle that content in powerful ways in relation to your own insights into what it takes to handle it in powerful ways. (p. 256)

Using powerful ways of teaching involves finding out what has to be done in particular cases, for particular learners and for particular objects of learning.

As the framework makes it possible to identify critical aspects of the object of learning, learning studies can reveal what is required for students to understand certain things in certain ways (Lo, 2012). Throughout the learning studies and supported by variation theory, a 'science of teaching' (Elliot, 2012) was developed as teachers

were given an opportunity to pose critical questions about the subject matter they were to teach, as well as about their own tacit and largely unexamined theories about the minds of learners and learning. By participating in the learning studies they became aware of things they had previously taken for granted; they became able to define critical aspects that they had not been aware of before; and they became able to design their lessons based on their findings. The teachers used the 'laboratory model' (Elliot, 2012) and variation theory in their search for critical aspects and worked out lesson plans that made it possible for their students to discern these critical aspects (Nilsson, 2014).

What is argued in this article is that the results of the PCK-tests reflect the teachers learning in the learning studies. However, some limitations of the study are important to acknowledge. For example, the results of this article concerns only four teachers. Further, the link between the teachers' changes and their participation in the three learning studies can always be problematized. Therefore, there is a need for further studies of how learning studies influence teaching strategies and teachers' PCK development. With these limitations in mind, we still conclude that in the interviews after the learning studies the teachers were able to articulate insights of the object of learning and how their students should become able to see and handle it. Moreover, in the video-recorded lessons they demonstrated a capability to handle the content in a more powerful way than before the learning studies. The conclusion is that the teachers have developed their PCK in line with how both Shulman (1986, 1987) and Marton (2014) define it.

Disclosure statement

No potential conflict of interest was reported by the authors.

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