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Upper Secondary Teachers' Knowledge for Teaching Chemical Bonding Models

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ABSTRACT

Researchers have shown a growing interest in science teachers' professional knowledge in recent decades. The article focuses on how chemistry teachers impart chemical bonding, one of the most important topics covered in upper secondary school chemistry courses. Chemical bonding is primarily taught using models, which are key for understanding science. However, many studies have determined that the use of models in science education can contribute to students' difficulties understanding the topic, and that students generally find chemical bonding a challenging topic. The aim of this study is to investigate teachers' knowledge of teaching chemical bonding. The study focuses on three essential components of pedagogical content knowledge (PCK): (1) the students' understanding, (2) representations, and (3) instructional strategies. We analyzed lesson plans about chemical bonding generated by 10 chemistry teachers with whom we also conducted semi-structured interviews about their teaching. Our results revealed that the teachers were generally unaware of how the representations of models they used affected student comprehension. The teachers had trouble specifying students' difficulties in understanding. Moreover, most of the instructional strategies described were generic and insufficient for promoting student understanding. Additionally, the teachers' rationale for choosing a specific representation or activity was seldom directed at addressing students' understanding. Our results indicate that both PCK components require improvement, and suggest that the two components should be connected. Implications for the professional development of pre-service and in-service teachers are discussed.

KEYWORDS

Pedagogical content knowledge; Chemical bonding; Models; Chemistry education; Students' understanding

Introduction

This study investigates the teaching of chemical bonding, one of the most important topics in upper secondary school chemistry courses. Various authors have concluded that students' difficulties in understanding chemical bonding are partly due to the inherent complexity of the topic but are also partly due to the way it is taught (e.g. Levy Nahum, Mamlok-Naaman, & Hofstein, 2013; Taber & Coll, 2002). As argued by Hattie (2009), teachers need to be more aware of the impact of their teaching on students' understanding, and

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attribute failure in students' understanding to their own teaching rather than to students' lack of ability or motivation (Nuthall, 2004). Chemical bonding is predominantly taught using models. However, the use of models in science education is problematic. Several studies show that students have difficulty understanding models in general, and chemical bonding models in particular (Grosslight, Unger, Jay, & Smith, 1991; Ingham & Gilbert, 1991; Justi & Gilbert, 2002; Özmen, 2004). For example, teachers and textbooks are not always explicit when using models (Drechsler & Van Driel, 2008; Gericke, Hagberg, Santos, Joaquim, & El-Hani, 2014), and the nature and purpose of models are often not discussed (Grosslight et al., 1991). This may explain why students tend to transfer macroscopic properties to particles (Othman, Treagust, & Chandrasegaran, 2008; Taber, 2001).

Hybrid models contain attributes from separate historical models with different theoretical backgrounds and pose an additional problem for model use in teaching science (Gilbert, 2007). Teachers and textbooks often use hybrid models in science education which may obstruct both teaching and learning (Gericke & Hagberg, 2007; Gericke et al., 2014; Thörne & Gericke, 2014). The matter is further complicated when teachers forget that they are communicating science via a model. In fact, teachers often present a model as though it were proven fact rather than theory (Treagust, Chittleborough, & Mamiala, 2002). This may be why students frequently consider the model an exact replica of the real thing (Grosslight et al., 1991; Ingham & Gilbert, 1991).

It is important for teachers to relay the purpose and nature of models, including their different states and uses, and their limitations. Teachers should also recall that several models may be used to explain a concept. These actions by teachers would avoid the problems caused by the use of models in science education. By extension, students would be allowed to gain a better understanding of scientific knowledge and the nature of science (Boulter & Gilbert, 2000; Drechsler & Van Driel, 2008; Gericke & Hagberg, 2007). Pedagogical content knowledge (PCK) for science teachers should incorporate the above actions concerning teaching with models.

Despite a broad range of studies on student understanding of chemical bonding models, little is known about whether teachers know how to teach them. The aim of this study was to investigate whether teachers know how to teach chemical bonding models (the models in focus are teaching models, defined by Gilbert, 2007), with a focus on their knowledge of student understanding, representations, and instructional strategies. The study was guided by the following research questions:

(1) What do teachers know about alternative conceptions and difficulties in understanding for students regarding chemical bonding?
(2) How do their representations of chemical bonding models and instructional strategies, as described by the teachers, address students' alternative conceptions and difficulties in understanding?

Pedagogical Content Knowledge

Shulman (1986, 1987) proposed the concept of PCK to bridge the gap between teachers' subject matter knowledge and their transformation of knowledge into instruction for students; and, also, to assess teacher competence. Shulman's original key components were:

(a) knowledge of students' specific learning difficulties, and (b) knowledge of instructional strategies and representations. Although many models of PCK have been proposed since Shulman's introduction (reviewed by Abell, 2007; Gess-Newsome, 1999; Kind, 2009), a majority include these two original components. In the PCK model by Magnusson, Krajcik, and Borko (1999), the first component concerns requirements for learning certain concepts, areas that students find difficult, approaches to learning science, and common alternative conceptions, whereas the second includes knowledge of representations and activities. The instructional strategies may be specific to subject or topic. Many researchers have used this PCK model in science education internationally (e.g. Berry, Loughran, & van Driel, 2008; De Jong, Van Driel, & Verloop, 2005; Nilsson & Van Driel, 2010). A recently presented model, the consensus model, originated from the PCK summit (an international gathering with researches interested and experienced in the field of PCK), was refined and presented by Gess-Newsome (2015). This model "identifies the overarching role of teachers professional knowledge and situates PCK within that model, including all of the complexity of teaching and learning" (Gess-Newsome, 2015, p. 30). A new category of teacher knowledge, the so-called topic-specific professional knowledge (TSPK), is included in the consensus model, which emphasize that content for teaching occurs at the topic level. Knowledge of student understanding, (content) representations, and instructional strategies are within this category considered separate components.

The consensus model is used as a framework in this study, and hereafter, the three key components regarding teachers are referred to as knowledge of students' understanding (KSU), knowledge of representations (KR), and knowledge of instructional strategies (KIS).

KSU, KR, and KIS are essential for several reasons. For example, a student's alternative conceptions can hinder comprehension of subsequent related concepts, thus obstructing effective learning (Taber, 1995), which indicates the importance for a teacher's knowledge of students' conceptions and difficulties in understanding. Teaching a given topic becomes more effective for the teacher with an improved view of students' difficulties in understanding and a well-stocked repository of representations and activities available for use (De Jong et al., 2005). Moreover, these components have proven critical for the interaction between the PCK components and, by extension, for the shaping of a teacher's PCK structure. The quality of PCK depends on coherent integration of the components as well as the strength of each individual component (Park & Chen, 2012).

Students' Difficulties Understanding Chemical Bonding Models Related to Teaching

Since we cannot see how atoms or other particles are held together, models of chemical bonding are required for understanding chemistry (Coll & Treagust, 2003). However, several studies have identified chemical bonding as a topic for which a wide range of difficulties in understanding and alternative conceptions exist (e.g. reviewed by Özmen, 2004; Taber & Coll, 2002), as summarized in Table 2. Research results have also shown that several of the more common alternative conceptions are retained at higher educational levels, that is, among university students (Coll & Treagust, 2002; Nicoll, 2001). This study focuses on teaching models of the main types of chemical bonding: ionic, covalent, and metallic.

Students' difficulties understanding chemical bonding are partly due to the way this topic is taught by teachers and presented in textbooks (e.g. Levy Nahum et al., 2013; Taber & Coll, 2002). Several factors can be seen as sources of difficulty: use of the octet rule and focus on electronic configurations, focus on presenting the atoms as separate, lack of explanation for why bonding occurs, anthropomorphic descriptions of chemical processes, and failure to explain that chemical bonds are due to electrostatic forces (Figure 1). Taber and Coll (2002) argue that if taught with these factors, students might generate a common alternative conceptual framework termed the *octet framework*, which then reinforces alternative conceptions and difficulties in understanding (Table 2). For example, if there is a failure to point out that electrostatic forces contribute to all chemical bonds, it could be a source for students identifying ionic bonding with electron transfer instead of electrostatic forces, which is a student's conception reported in several studies (Robinson, 1998; Taber, 1997; Taber & Coll, 2002); and regarding covalent bonding, the conception that the shared electron pair in itself *is* the bond, and the electron pair holds the atoms together *because* they then get noble gas shell (Taber & Coll, 2002). The common representations of ionic bonding in terms of electron transfer could also lead

Figure 1. Factors that may contribute to development of the octet framework, which increases the students' alternative conceptions and difficulties in understanding.

to the conception that ionic compound contains molecules (Barker & Millar, 2000; Othman et al., 2008; Taber & Coll, 2002) or ions pairs to be seen as molecules (Othman et al., 2008; Taber & Coll, 2002). For example, failure to show that electrostatic forces contribute to all chemical bonds could lead to students identifying ionic bonding with electron transfer instead of electrostatic forces, a commonly reported alternative conception (Robinson, 1998; Taber, 1997; Taber & Coll, 2002). With regard to covalent bonding the frequent alternative conception, as a result of this failure, is that the shared electron pair in itself *is* the bond, and the electron pair holds the atoms together *because* they then obtain a noble gas shell (Taber & Coll, 2002). The common representation of ionic bonding in terms of electron transfer could also cause the conception that ionic compounds contain molecules (Barker & Millar, 2000; Othman et al., 2008; Taber & Coll, 2002), or it could lead to ion pairs being seen as molecules (Othman et al., 2008; Taber & Coll, 2002).

An additional factor is that ionic and covalent bonds are often presented as a dichotomy. This could be why concepts such as bond polarity, molecule shapes, and molecule polarity are unclear to students (Harrison & Treagust, 1996; Peterson, Treagust, & Garnett, 1989; Taber & Coll, 2002). This factor could also explain the existence of the alternative conceptions that: no bonding at all exists in metals; there is some form of bonding but not proper chemical bonding; or metals have covalent and/or ionic bonding (Taber, 2001, 2003).

It can be problematic for teachers to find out effective instructional strategies aiming at revealing students' understanding. In order to identify students' alternative conceptions and monitor the development of their understanding, Van Driel and Gräber (2002) suggest teachers to develop questionnaires by using items from research literature, especially when there is a large amount of research-based knowledge in the specific topic. Vikström (2014) also indicates that, even when teachers are well aware of students' difficulties in understanding a specific topic, they might be unable to express those difficulties in detail (Vikström, 2014). Hence, it can be difficult for teachers to define critical aspects with regard to the specific topic and become able to plan their lessons based on these aspects. It is pointed out as challenging but also important for teachers to find representations of models and instructional strategies to make complex ideas accessible but also scientifically valid, which provides a foundation for students' future learning (Nilsson, 2014). Besides, another challenge for science teachers is to simplify scientific concepts by relating them to everyday concepts without causing problematic interpretations among students (Nilsson, 2014).

Method

Participants

Ten teachers from seven upper secondary schools in Central Sweden volunteered to participate in the project (referred to hereafter as T1–T10). All the teachers are qualified (with a degree) to teach upper secondary school chemistry in Sweden. More information about the teachers is given in Table 1. The topic "chemical bonding" is included in Swedish curricula (Skolverket, 2011), which emphasizes the importance of using models to teach science.

Table 1. Information about the participating teachers, identified as T1–T10. The teachers' schools are designated A–G

Teacher	Gender	Years of teaching experience		School
		Total	*Chemistry in upper secondary school*	
T1	Male	36	10	A
T2	Male	10	5	B
T3	Male	10	10	C
T4	Male	35	20	C
T5	Female	15	15	D
T6	Male	7	7	D
T7	Female	>30	30	D
T8	Female	5	5	E
T9	Male	19	10	F
T10	Female	3	3	G

Study Design and Data Resources

The Lesson Preparation Method developed by Van Der Valk and Broekman (1999), also successfully implemented by several researchers (De Jong, 2000), was the main approach used in this study. It consists of two main parts: (a) teachers' prepared lesson plans and (b) individual interviews with the teachers. This study was designed as a small-scale explorative study, and in addition to The Lesson Preparation Method, the textbook analysis was included. The study consisted of three main steps: (1) a preliminary analysis of the chemistry textbooks used by the teachers when teaching chemical bonding and the lesson plans that were prepared by the individual teachers; (2) semi-structured interviews with the chemistry teachers, building on information gathered in step (1); (3) in-depth analysis of the textbooks, lesson plans, and interviews. The purpose of step (1) was to prepare specific questions for the interviews with the teachers (step 2). The in-depth analysis of the textbooks has been reported in a separate paper (Bergqvist, Drechsler, De Jong, & Rundgren, 2013).

In the lesson preparation task, the participating teachers were individually asked to prepare and submit a lesson plan that was 2–4 pages long including representations and instructional strategies, 1–2 weeks before an interview with the first author. The teachers were asked to consider their motives for choosing specific representations and instructional strategies in the lesson plans. They had the choice of submitting an already-written lesson plan or writing a new one for the study. Each teacher selected the number of lessons for his/her plan and no limit was imposed on the kind of sources used for plan preparation.

The semi-structured interviews consisted of questions about teachers' KSU of chemical bonding models, teaching strategies, and their motives for choosing specific representations and instructional strategies. Similar questions were sent by email to the teachers about two weeks before the interview to allow them to prepare (see Interview Guide Appendix A for specific questions). The interviews were audio-taped. During the interviews, the teachers were asked to reflect on their lesson plans and articulate reasons for their instructional decisions. The questions were generated from research literature on student understanding, and from brief analyses of the teachers' lesson plans and the textbooks (step 1).

The Analytical Framework for Depth Analysis and the Analytical Process

The teachers' statements about their perceptions of students' understanding of chemical bonding were compared to statements on students' understanding reported in the literature (Table 2). Alternative conceptions and difficulties in understanding were classified according to bonding type: general, ionic, covalent/polar, and metallic.

Table 2. Students' alternative conceptions of, and difficulties in understanding regarding, chemical bonding stated by the teachers, as compared to examples in research literature. Possible sources of these conceptions/difficulties are indicated when reported by research literature

Students' conception (C)/difficulty in understanding (D)	Research literature	Teacher	Possible sources of students' conceptions and difficulties in understanding
General bonding:			
Regard models as an exact replica of the real thing (C)	Grosslight et al., (1991), Ingham and Gilbert (1991)	T6	
Bonds form so atoms can obtain complete octets (C)	Taber and Coll (2002)	T5	Use of octet rule and focus on electronic configurations (Taber & Coll, 2002)
Bonds are sticks (C)	Butts and Smith (1987)	T2, T3, T5, T6	Ubiquitous use of ball and stick models (Butts & Smith, 1987)
Electrons did not move within bonds (C)	Nicoll (2001)	T5, T6	
The reactants in chemical processes are individual unbound atoms (C)	Taber and Coll (2002)		Focus on separate atoms when representing chemical reactions (Taber & Coll, 2002)
Intermolecular bonding is stronger than intramolecular bonding (C)	Goh, Chia, and Tan, (1994) and Peterson et al. (1989)		
Comparing the strength between the different types of bonding (D)		T1, T6	
The difference between intra- and intermolecular bonding is unclear (D)	Taber and Coll (2002)	T1, T3, T5, T6, T7, T8, T9, T10	Ionic and covalent bonding presented as a dichotomy (Taber & Coll, 2002); failure to present that chemical bonds may be due to electrostatic forces (Taber & Coll, 2002)
Use the right concept but wrong explanation (D)	Nicoll (2001)	T5, T8	
Could not provide a correct explanation for bonding phenomena and/or why bonding occurs (D)	Nicoll (2001)	T8, T9	
Relate energy to bonding (D)		T5	
Conceptualize the ionic-covalent continuum (D)	Taber and Coll (2002)	T1, T5, T7, T9	Ionic and covalent bonding presented as a dichotomy (Taber & Coll, 2002)
Ionic bonding:			
Describing ionic bonding as the transfer of electrons (C)	Robinson (1998) and Taber and Coll (2002)		Ionic bonding presented in terms of electron transfer (Taber & Coll, 2002)
Bonds are only seen to exist between ions that have transferred electrons (C)	Robinson (1998) and Taber (2003a)		Ionic bonding presented in terms of electron transfer (Taber & Coll, 2002)
The ion lattice consists of ion pairs, which are regarded as molecules (C)	Othman et al. (2008) and Taber and Coll (2002)		Order of introducing types of bonding (Taber & Coll, 2002); bonded non-molecular materials presented as involving discrete molecules (Taber & Coll, 2002)
Molecules exist in ionic compounds (C)	Barker and Millar, (2000) and Othman et al. (2008)	T6, T7, T8	Order of introducing types of bonding (Taber & Coll, 2002); bonded non-molecular materials presented as involving discrete molecules (Taber & Coll, 2002)

(*Continued*)

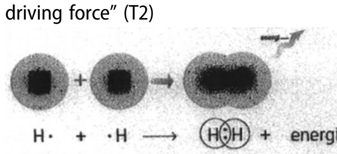
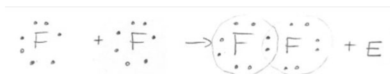
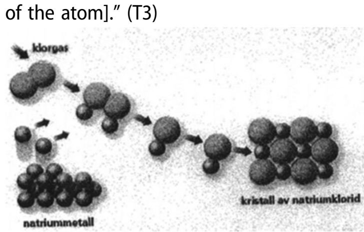
Table 2. Continued.

Students' conception (C)/difficulty in understanding (D)	Research literature	Teacher	Possible sources of students' conceptions and difficulties in understanding
The electrostatic interactions between the ions in ionic lattice are unclear (D)	Robinson (1998) and Taber and Coll (2002)		Failure to present that chemical bonds may be due to electrostatic forces (Taber & Coll, 2002)
Covalent/polar covalent bonding:			
Sharing electrons is covalent bonding (C)	Taber and Coll (2002)	T2	Covalent bonding presented in terms of electron sharing (Taber & Coll, 2002)
The electron pair in itself constitutes the covalent bond (C)	Taber and Coll (2002)		Covalent bonding presented in terms of electron sharing (Taber & Coll, 2002)
Covalent bonds are weak (C)	Barker and Millar (2000)	T1	
Covalent bonds are between molecules (C)		T1	
Difficulty conceptualizing polar covalent bonding (D)	Taber and Coll (2002)	T9, T10	Ionic and covalent bonding presented as a dichotomy (Taber & Coll, 2002)
Difficulty conceptualizing the ionic-covalent continuum (D)	Taber and Coll (2002)	T1, T5, T7, T8	Failure to present that chemical bonds may be due to electrostatic forces (Taber & Coll, 2002); ionic and covalent bonding presented as a dichotomy (Taber & Coll, 2002)
Difficulty conceptualizing the terms "polar" and "non-polar" (D)		T2, T3, T8, T9	
Difficulty conceptualizing the term "polar molecule" (D)	Harrison and Treagust (1996)	T1, T2, T4, T5, T7, T8, T9, T10	
Metallic bonding:			
Molecules or ions are present in metallic structures (C)	de Posada (1999) and Taber (2003b)		Ionic and covalent bonding presented as a dichotomy (Taber & Coll, 2002); order of introducing types of bonding (Taber & Coll, 2002)
There are covalent or ionic bonds in metals (C)	Taber (2001); Taber (2003b)		Ionic and covalent bonding presented as a dichotomy (Taber & Coll, 2002)
Metallic bonding is a variation of the ionic or covalent bond (C)	Taber and Coll (2002)		
There is no bonding at all in metals (C)	Taber (2001)		Ionic and covalent bonding presented as a dichotomy (Taber & Coll, 2002)
There is some form of bonding in metals, but it is not "proper" chemical bonding (C)	Taber (2001)		Ionic and covalent bonding presented as a dichotomy (Taber & Coll, 2002)
Difficulty conceptualizing metal bonding(D)	Taber (2001, 2003b)	T1	
Difficulty understanding electrostatic forces between components of metals (D)	de Posada (1999)		Insufficient explanation that cations and the electron cloud act reciprocally (de Posada, 1999)

Representations of models and *instructional strategies* that emerged from lesson plan analyses and the interviews were used as two main categories. The *representations of models* category were further divided into 11 subcategories (Table 3), which were used for in-depth analysis of the textbooks (Bergqvist et al., 2013). These subcategories were generated from: a literature review of reports on students' understanding of models in general and chemical bonding models (Drechsler & Van Driel, 2008; Gericke & Hagberg, 2007; Gilbert, 2007; Taber & Coll, 2002); data from textbook chapters on chemical bonding; and the literature used to identify sources of student difficulties in understanding. The first eight subcategories were classified into three modes of representation: verbal, symbolic, and visual (Gilbert, 2007).

The *instructional strategies* category was divided as follows: general, subject-specific, topic-specific; and further classified as either teacher-centred or student-centered.

Table 3. Examples of representations of chemical bonding models that might be sources of students' difficulties understanding according to the categories used in the analysis. The teachers are referred to as T1–T10, and the quotes are translated from Swedish. The headings of categories 3, 6, and 9 are not, by themselves, sources of difficulties; *failure to provide any* reason, or *an appropriate* reason for why bonding occurs, *not* presenting chemical bonding as due to electrostatic forces, and *not* explaining a model's nature and purpose may count as sources

Categories used to identify representations that might be sources for learning difficulties	Teacher	Examples
(1) Use of the octet rule and focus on electronic configuration	T1–T10	"All elements want to achieve noble gas structure, i.e. get eight electrons in the outer shell" (T8)
(2) Focus on separate atoms when representing chemical reactions	T1–T10	 (T5)
(3) Reason for why bonding occurs		
(a) Octet rule	T1–T10	"One talks about achieving noble gas structure, that is some kind of driving force" (T2)
(b) Energy changes	T1, T2, T3, T4, T5, T6, T8	 (T8)
(4) Anthropomorphism and chemical processes	T1–T10	"That they [atoms], want to be pleased, sort of, we use that often." (T8)
(5) Chemical bonding presented in terms of (a) electron transfer	T1-T10	 (T5)
(b) electron sharing	T1-T10	 (T5)
(6) Chemical bond due to electrostatic forces		
(a) ionic	T1-T10	"Ionic crystals are held together by attraction between the positive and negative ions." (T5)
(b) covalent and polar covalent	T4, T8, T10	
(c) metallic	T10	
(7) Attributes from different historical models merged into hybrid models	T1, T2, T3, T5, T7, T8	"Well, when you write, it is the classic one [Bohr's atomic model], but when you talk it is more like that [quantum-mechanical model of the atom]." (T3)
(8) Bonded non-molecular materials presented as involving discrete molecules	T2, T8	
(9) Teaching the models' nature and purpose		
	T2, T3, T4	"We are working with models, which sort of, may not be telling the whole truth, but telling the truth in different ways. One model has some advantages and disadvantages compared to others." (T3)
(10) Order of introducing types of bonding	T1, T2, T4, T5, T6, T8, and T9	Ionic, covalent, polar, and metallic bonding
(11) Use of typical examples	T1–T10	Ionic bonding: NaCl
	T1–T10	Covalent bonding: H_2

Statements in which teachers explicitly explained that a specific representation or *instructional strategy* was used to promote student understanding were classified as a connection between teachers' KSU and KR and KIS.

During lesson plan analyses in step 3, analytical units included paragraphs, which were listed as verbal modes of *representations of models*, and formulae, graphs, etc., which were listed as symbolic/visual modes. The analytical units were copied into a grid constructed with the 11 categories mentioned above, with one separate grid for each type of bonding.

For analysis of the interviews, also during step 4, the first author transcribed the audio-taped interviews verbatim using the Transana software, in which the written transcripts are connected to the audio (or video) recording. The analytical units were paragraphs which varied in length because of a focus on content.

The entire data analysis process was iterative. The analytical process and critical excerpts of data were discussed, and consensus on these was achieved among four senior researchers in science education (the authors and an additional researcher). At the time of writing, two of the researchers were professors of science education, one was a senior lecturer, and one was a PhD student. The first and second authors were also qualified school chemistry teachers.

Results

Teachers' KSU

All but one of the teachers (T8) considered "chemical bonding" a topic that students find hard to understand. Several examples of students' alternative conceptions and difficulties were stated, mostly regarding covalent/polar bonding. The teachers explicitly said that ionic bonding was the least problematic type of bonding for their students to understand. For ionic bonding only one alternative conception was mentioned: molecules exist in ionic compounds. Besides, only one teacher gave examples of students' difficulties conceptualizing metallic bonding, and none of the teachers specified conceptions/difficulties for *all* types of bonding. T3 was, notably, the only teacher who stated that he occasionally discussed some common alternative conceptions with his students.

A majority of teachers' examples of students' alternative conceptions and difficulties in understanding were similar to examples found in the literature. However, less than half of the examples in the literature were given by the teachers participating in the study (Table 2).

Although the teachers could give examples of students having difficulty understanding the topic, they had some trouble specifying the difficulties themselves. For almost every request to specify students' alternative conceptions and difficulties understanding chemical bonding, the teachers became silent for a while before answering. When the teachers then tried to reflect on their students' difficulties, they sometimes were able to give examples:

> I don't know that. I am unsure of how they … what problems they have, so to speak … just that they make mistakes. If they consider that the covalent bonding is … is the bonding between the molecules, maybe … instead of in the molecule … probably they think so. (T1)

There were also occasions when the teachers explicitly said that they did not know what the difficulties were, even though some of the teachers stated that KSU is important for their teaching. For example:

> Well, that … I find it difficult to answer. But I don't know … and that's something you should know, to be able to continue [to teach]. (T6)

Teachers' Representations of Chemical Bonding Models and Connections between KSU and KR

Most of the participating teachers introduced the different types of chemical bonding in the following order: ionic, covalent, polar covalent, metallic, and intermolecular. We identified numerous examples of representations that might be a source of difficulty for student comprehension, according to the research discussed in earlier sections. Examples of these representations, according to each category used in the analysis, are given in Table 3. Bergqvist et al. (2013) describe how such representations of models of chemical bonding in textbooks might lead to students' difficulties in understanding. For example, all of the teachers commonly *used the octet rule and focused on electronic configurations* to explain all types of chemical bonding except metallic, for which it was not mentioned at all. The octet rule was also explicitly mentioned as *a reason for bonding* by all teachers. They explicitly used the term 'octet rule' or phrased the same concept in some way, for example, that the atoms achieve an octet of electrons, full shells, or noble gas shell/structure when bonds or ions are formed (see Table 3, Category 1 and 3a). *Anthropomorphic descriptions* were also common and used in a large variety of ways. For example, personification was used to describe atoms which were said to *fight* for, have a *hungry feeling* for electrons, *not share fairly, share like brothers*, and *be stronger* or *more capable to pull* electrons than others. Atoms were also said to *like* electrons, be able to *feel* electrons around them, *be pleased*, or *be jealous*. Only one teacher thought it important not to "stick to that kind of language".

In addition, the teachers *focused on individual atoms* when presenting ionic, covalent, and polar covalent bonding; these types of bonding were introduced with a hypothetical, fictional account of the origin of the bonding. That is, *ionic bonding was presented in terms of electron transfer* by presenting the formation of ions constituting the ionic compound (Table 3, Categories 2 and 5a), and covalent and polar covalent were introduced by presenting the formation of a molecule (Table 3, Categories 3b and 5b). In other words, the teachers presented the bonding types in terms of interactions between individual atoms, when the reactants are actually composed of molecules or lattice structure. Moreover, all the typical examples used to introduce ionic bonding demonstrated it as the result of electron transfer.

We found representations of *chemical bonding being due to electrostatic forces*, though this was presented alongside the octet rule. However, the explicit term 'electrostatic forces' was seldom used. Terms used instead were 'attraction' or 'attraction forces' (Table 3, Category 6). Only two teachers explicitly mentioned that *all* types of bonding are attractions between 'positive and negative' charges, and we identified only *one* non-verbal representation as chemical bonds being due to electrostatic forces, specifically in the context of covalent bonding. On the one hand, all of the teachers represented that ionic bonding is due to electrostatic forces, but ionic bonding was presented, or even defined, in terms of electron transfer between atoms, that is, the formation of ions, *driven* by the octet rule. On the other hand, we found few representations of covalent, polar covalent, and metallic bonding that could be interpreted as bonding due to electrostatic forces (only one representation of metallic bonding in all). Sometimes ionic and covalent bonds were even presented as opposites to each other with respect to electrostatic forces, with the octet rule given as the reason for bonding:

> I talk about obtaining noble gas structure, that is some kind of driving force [covalent bonding], that's what atoms want, that students can imagine, can understand […] whilst in ionic bonding it is plainly a physical phenomenon that plus and minus attract each other. (T2)

Another possible *reason why bonding occurs*, according to the teachers, was to achieve a lower state of energy or a stable state. As with electrostatic forces, this was not explicitly stated as a reason for bonding, and was mainly explained in connection with the fulfilment of the noble gas structure. For example:

> I try to explain, they want to achieve noble gas structure and when they get there, they come to a lower energy level, and they get more stable. (T8, covalent bonding)

We also identified examples of representations where energy was released in connection to chemical reactions (Table 3, Category 3b).

All the teachers presented covalent and polar covalent bonding in terms of *electron sharing*, that is, as electrons shared by two atoms in a molecule. For example, as shown in Table 3 Category 5b, and in verbal mode, the electron pair was said to be shared, equally or unequally, or the shared electron pair *itself* was presented as the covalent bond. For example:

> One would say that it is the electron pair which is this bond—that is what makes them hold together. (T9)
> So if one shares [electrons] with someone else, one gets eight, that is, sort of, what covalent bonding is. (T2)

We also identified examples of *hybrid models*. Several teachers stated that they used Bohr's atomic model in visual modes but in verbal mode, they also added attributes from models based on quantum mechanics. For instance, the probability that the electrons are located between the nuclei (valence bond theory); electron density between the atoms (molecule orbital theory); and the electrons of atoms described as an electron cloud (quantum-mechanical model of the atom). As one teacher, T3, said:

> Well, when you write, it is the classic one [Bohr's atomic model], but when you talk it is more like that [quantum-mechanical model] of the atom.

Only three of the teachers explicitly mentioned that, in the past, they would *teach about the nature and purpose of models* of chemical bonding, though mainly about the nature (T2, T3, and T4). For example, they said that they used to describe models as "not telling the whole truth" (T2), "not quite correct" (T3), or "simplified versions" (T4). One purpose of models mentioned was "a way to explain the reality" (T3). The teachers also mentioned that a concept can be explained in several ways, and that models have limitations and were developed during history.

In contrast to demonstrating chemical bonding, all but two of the teachers mentioned that when discussing the structure of atoms using Bohr's atomic model, they used to point out that it is only a model and that there are not actually orbits around the core of the atom.

The teachers gave very few explicit reasons for the use of a specific representation, but their examples included: "used in textbooks", seems "logical" or "good," or "it works." The teachers were aware that many students found this topic challenging and they were able to give examples of students' difficulties. However, only one statement by a teacher explicitly described students' difficulties in understanding as a factor for deciding how to present chemical bonding. The issue that the representation itself could be a source of students' difficulties was mentioned mainly with regard to the concrete mode of representing the ionic lattice.

Teachers' Use of Instructional Strategies and Connections between KSU and KIS

Most of the instructional strategies were generic and demonstrated pedagogical knowledge, that is, they were neither subject- nor topic-specific. These strategies were: (1) lecturing, (2) showing video-films or screen clips, (3) introducing the lesson with major questions, (4) using several typical examples, (5) pointing out the circumstance or concept several times, and (6) solving textbook tasks. Connections between KSU and KIS were identified when strategy 3 (T6), 4 (T8), and 5 (T1, T4, and T10) were explicitly described as strategies that were used to address difficulties in understanding among the students.

The only subject-specific strategies described by the teachers were teacher demonstrations and practical laboratory work. Moreover, only two topic-specific strategies, that is, specific to chemical bonding, were mentioned: the teacher-centred strategy 'showing three dimensional models of molecules or ionic lattices' (used by all the teachers); and the student-centred strategy 'building models of molecules' (mentioned by only five of the teachers). The use of three-dimensional models of molecules or ion lattices was contradictive. This strategy was most frequently used to demonstrate ionic bonding, the type of bonding that the teachers considered the least difficult for students to understand. Only one teacher used this strategy to introduce covalent and polar covalent bonding, the types of bonding that comprised most of the examples of students' difficulties. However, several of the teachers said they showed models of molecules when teaching about polar molecules, a concept that the teachers highlighted as difficult to understand (see Table 2). We identified explicit connections between KSU and KIS for only two of the teachers who used this particular strategy to address students' difficulties understanding bonding.

The other topic-specific strategy described was used to teach about polar molecules. However, only two of the five teachers who used this strategy said that they did so because it improved student comprehension.

The strategies used for ascertaining students' understanding were neither subject- nor topic-specific: teachers asking oral questions during lessons, teachers administering written tests, students asking questions of the teacher during lessons, and students asking questions of the teacher when completing textbook tasks. The most common strategy involved teachers asking oral questions during the lecture and students asking questions when completing textbook tasks. However, several teachers stated that ascertaining whether all the students understood using these strategies is problematic because it is impossible to question all students, and not all students ask questions.

The role of reflection on the teachers' KIS was also evident. When the teachers reflected on student understanding during the interview, they sometimes came up with new strategies for exploring their students' understanding. For example, one teacher decided to ask his students, in the future, to write about how they imagine a hydrogen molecule looks.

Discussion and Implications

Teachers' KSU Can Be Improved

Most of the students' alternative conceptions and difficulties identified by teachers in this study have been discussed in the literature. Moreover, their students are likely to have the same difficulties understanding as previously reported, especially since we discovered that the teachers presented chemical bonding models in a way that might cause alternative conceptions and comprehension difficulties (e.g. Taber & Coll, 2002). However, several of the alternative conceptions and difficulties reported in the literature were *not* mentioned by the study participants. Furthermore, on several occasions, the teachers were unable to specify students' difficulties and hesitated when trying, even though they sometimes gave examples after some reflection. It seems like the teachers, by means of reflection, could give examples of students' difficulties, but their statements revealed that they seldom do so, maybe because of lack of time, tradition, or unawareness. This demonstrates that the teachers' KSU needs improvement. This component of the teachers' PCK is considered important for making effective teaching and the ability to address students' understanding (De Jong et al., 2005; Kind, 2009; Taber, 1995).

The Teachers' Representations of Chemical Bonding Models Can Cause Difficulties in Understanding

Our results revealed that the teachers used representations which can be sources of the octet framework and could further impede learning (Taber & Coll, 2002), that is, they can cause difficulties for students attempting to understanding the topic (for detailed descriptions, see Bergqvist et al., 2013). However, the teachers seemed to be generally unaware of how representations could contribute to students' difficulties in understanding. For example, when there is a lack of discussion on why chemical reactions occur, the octet rule is frequently used and thereby presents a feasible alternative explanation that fails to point out that electrostatic forces contribute to all chemical bonds. This may result in an assumption that the octet rule is the reason for bond formation (Taber & Coll, 2002). Moreover, the presentation of ionic bonding in terms of electron transfer between atoms and covalent bonding in terms of electron sharing, used by all of the teachers, has been strongly criticized because both can lead to multiple alternative conceptions (Taber & Coll, 2002). Taber and Coll argue that this problem can be avoided by using a teaching model that emphasizes electrostatic interactions for *all* bonding types, rather than the transfer and sharing of electrons; this argument was also demonstrated by a recent study by Lee and Cheng (2014). The teaching model would be 'at an optimal level of simplification' (Taber & Coll, 2002 p. 218), that is, being kept as simple as possible while still being scientifically correct, which provides a foundation for students to develop later on in their learning process (Taber & Coll, 2002). If this model is used to explain ionic, covalent, and metallic bonds, the students will be better prepared to understand intermolecular forces, electronegativity, and bond polarity.

A possible reason why bonding occurs, according to the teachers, is to achieve a lower state of energy or a stable state. However, none of the teachers used the common representation in terms of a plot of potential energy versus inter-nuclear distance for describing chemical bonding. This representation shows the exothermic nature of bond formation and reinforces the idea that two bonded atoms are lower in energy than when they are not bonded, hence making an appropriate contribution to the discussion on why chemical reactions, and bonding, occur.

The teachers in this study frequently used anthropomorphic explanations to explain chemical processes. These can be an additional source of components of the octet framework (Taber & Coll, 2002). Therefore, we recommend that teachers use anthropomorphic explanations less frequently. Instead they should clearly relate to their students that these explanations provide a starting point for conceptualizing chemical bonding; in other words, it is “a bit like this”.

Only three of the teachers stated that they teach about the nature and purpose of models of chemical bonding, which are emphasized in the curricula and considered important for overcoming the difficulties associated with models (e.g. Boulter & Gilbert, 2000; Drechsler & Van Driel, 2008; Gericke & Hagberg, 2007). Moreover, several of the teachers merged attributes from different historical models and thereby created hybrid models. These hybrid models may cause difficulties for both teaching and learning (e.g. Gericke & Hagberg, 2007; Justi & Gilbert, 2000). None of the teachers remembered models they learned while studying chemistry at University for use in explaining chemical bonding, other than those presented in the textbooks. This may explain why teachers do not point out, for example, that electron sharing is one of several models for explaining covalent bonding. They may also be unaware that they transferred and merged attributes from separate historical models, thus forming hybrid models, which they used in their teaching, and which are presented in the textbooks (Bergqvist et al., 2013). However, the teachers were clearly mindful of the model of the atom based on quantum mechanics, also presented in all the textbooks. This mindfulness might explain why the teachers discussed the nature of models mainly for Bohr’s atomic model, by stating in some way that it “is only a model”. Therefore, we conclude that teachers need to continuously remind themselves of more advanced models in order to think critically about their use of textbooks, and be able to point out limitations of the models presented. We think that teachers need to be aware of: *how* the models are presented; *which* representations might be sources of students’ learning difficulties; and the nature of models and their related purposes.

The Teachers’ Repository of Instructional Strategies Can Be Enlarged

PCK is seen as the teachers’ knowledge used to benefit students’ understanding (e.g. Kind, 2009; Loughran, Milroy, Berry, Gunstone, & Mulhall, 2001), and the more instructional strategies the teachers possess, the more effective the teaching can be (De Jong et al., 2005). Our results revealed that most of the instructional strategies practiced by study participants were neither subject- nor topic-specific. In fact, only two topic-specific instructional strategies were mentioned. Moreover, one of the two topic-specific instructional strategies was mentioned in association with ionic bonding, which the teachers regarded as the bonding type that was the *least* difficult for students to understand. In addition, the strategies used to ascertain students' understanding, which must be considered important in order to address students' understanding, were deficient for determining whether *all* the students understood the topic. We can conclude that the teachers' repository of instructional strategies can be enlarged to include strategies that better address students' understanding of chemical bonding. However, we are aware of that teachers may display more knowledge in practice than they are able to articulate in an interview, which has been mentioned by other researchers (Rollnick, Bennett, Rhemtula, Dharsey, & Ndlovu, 2008). We might have elicited more knowledge if we had used another tool to examine the teachers' knowledge, such as Content Representation, CoRe, a tool to make PCK explicit by systematic reflection on teaching practice which was devised by Loughran, Mulhall, and Berry (2004).

Deficient Connections Between Knowledge of Understanding and Representations and Instructional Strategies

All but one of the participant teachers had taught Chemistry in an upper secondary school for at least five years. The teachers were aware that many students found chemical bonding challenging. One may assume that PCK develops over time and through experience (e.g. Loughran, Berry, & Mulhall, 2006). Therefore, one might have expected the teachers to consider students' difficulties when deciding how to teach chemical bonding. However, few teachers' statements explicitly described that the reason for using a specific representation or instructional strategy was to address student understanding. This corroborates a study by Drechsler and Van Driel (2009) which did not reveal any correlation between teachers' knowledge of students' comprehension and their methods for teaching the models for acid and bases. Another set of results reported by Van Driel and Verloop (2002) found that teachers' knowledge of students is marginally linked to instructional strategies, which also supports our findings. Moreover, the teachers were generally unaware of how the representations they used could contribute to difficulties in understanding among students, and they did not reflect extensively on their teaching practices. The lack of reflection is indicated by teachers' statements describing the study's interview as one of few occasions in several years when they discussed and reflected on their teaching; they considered these self-assessing actions important but seldom have time to complete them. As demonstrated, the reflection during the interview sometimes made the teachers able to describe students' difficulties, and also to discover new instructional strategies. Teaching experience is critical for the development of PCK because it promotes integration among the PCK components (Friedrichsen et al., 2009). However, as our results demonstrate, teaching experience without reflection does not necessarily develop the teachers' PCK. Teachers' reflection on their teaching experiences and students' difficulties is important and crucial for developing PCK; this has been addressed by several researchers (Drechsler & Van Driel, 2008; Nilsson, 2009; Tuan, Jemg, Whang, & Kaou, 1995). If teachers are encouraged to share their experiences and to interpret, value, and learn through reflection, the resulting experiences can contribute to development of PCK (Nilsson, 2009). Teachers should ask themselves *why* they choose a specific representation or activity and be able to give a reason for their choices (Wickman, 2014).

It is therefore important to create opportunities for teachers to systematically reflect on their teaching practices together with colleagues in order to developing their PCK. Our results emphasize the need for continuous development of teachers' expertise beyond their initial training during teacher education programs (Harrison, Hofstein, Eylon, & Simon, 2008). In their study, Park and Chen (2012) found that KSU and KIS (in their study, KR and activities were included in the component instructional strategies) are central to, and impact the integration between, all the components of PCK. Therefore, the individual components as well as the connection between them should be central objects for improvements. For example, opportunities should be created for teachers to investigate students' understanding of chemical bonding and then choose appropriate representations and instructional strategies that help the students' understand the topic. The teachers' ability and need to reflect on their own practices is a vital aspect of any continuing professional development program (Harrison et al., 2008; Taitelbaum, Mamlok-Naaman, Carmeli, & Hofstein, 2008). More research is required to discover effective models for systematic reflections on teaching practices that promote teaching long-term. Moreover, our results indicate a gap between previous research results concerning students' understanding of chemical bonding models and teaching practices. Therefore, to bridge this gap, there is a need to improve cooperation between researchers in science education, teacher educators, and pre- and in-service teachers. A Learning Study Framework where research results from science education research have been used as a resource can be a way to integrate research results into teachers' teaching practice (Vikström, 2014). We think that the results of this study could benefit in-service as well as pre-service teachers and teacher education, and they demonstrate the need for professional development regarding the teaching of chemical bonding models as well as models in general within science education.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix A: Interview guide

Briefing

Introduction, presentation of myself and the research project
Permission to use tape recorder
Questions from interviewee, regarding the interview procedure

Briefing

What are your teaching experience, years, and schools?
What do you think about teaching

- chemistry?
- chemical bonding?

Main

Lesson Plans

In what way does this lesson plan reflect your usual teaching of chemical bonding?
What sources do you use for planning lessons?

- What was your reason to choose [if relevant] the particular example, drawing, explanation, scheme, activities in your lesson plan?

Textbook

How do you use the textbook?
In your opinion, what is the importance of the textbook, for you and the students?
What do you think about the explanations used by the textbook of the different types of chemical bonding? (Depending of the answer, some excerpts from the book will be discussed).

Students' Understanding

What is your experience of the students' understanding of chemical bonding?
How do you handle this?

Additional Models of Chemical Bonding

What models to explain chemical bonding do you remember, other than mentioned in the textbooks and in the lessons plan?

Debriefing

How did you experience the interview?
Do you want to add anything or ask any questions with the tape recorder off?
May we use the recording?