Models of Chemical Bonding

Representations Used in School Textbooks and by Teachers and their Relation to Students' Difficulties in Understanding

Anna Bergqvist

Faculty of Technology and Science

Chemistry

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Abstract

This thesis focuses on how school textbooks and teachers present models of chemical bonding in upper secondary schools in Sweden. In science, as well as in science education, models play a central role, but research has shown that they often are difficult for students to understand. In science education, models are presented to students mainly through textbooks and teachers, and textbooks influence teachers' teaching. The aim of this thesis was to investigate how textbooks and teachers present models of chemical bonding in relation to students' difficulties in understanding. To analyze representations of models, an analytical framework based on research reports about students' difficulties in understanding related to models in general and chemical bonding in particular was developed. The chapters of chemical bonding in five chemistry textbooks were analyzed. Further, ten chemistry teachers' lesson plans about chemical bonding and semi-structured interviews with the teachers concerning their teaching were analyzed. This analysis concerned teachers pedagogical content knowledge (PCK) of teaching chemical bonding, with focus on knowledge of students' difficulties in understanding and teaching strategies that take these difficulties into account. The results show that the teachers could specify examples of students' difficulties in understanding, but the teaching strategies to promote the students' understanding were limited. This indicates a deficient interaction between knowledge of difficulties in understanding and teaching strategies, two essential components of teachers' PCK. Further, the models of chemical bonding represented in the textbooks and by the teachers might cause students' difficulties in understanding. This indicates a gap between research about students' difficulties in understanding and teaching practices as well as development of textbooks. Further, the teachers' representations of models were strongly influenced by the textbooks. Implications for textbook authors, pre-service as well as in-service teachers are addressed.

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List of papers

Paper I

Representations of chemical bonding models in school textbooks - help or hindrance for understanding?
Anna Bergqvist, Michal Drechsler, Onno de Jong, Shu-Nu Chang Rundgren

Submitted to *Chemistry Education Research and Practice*

Paper II

Swedish upper secondary teachers' pedagogical content knowledge to teach chemical bonding
Anna Bergqvist, Michal Drechsler, Onno de Jong, Shu-Nu Chang Rundgren

Submitted to *Research in Science Education*

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Introduction

The importance of science and technology in the present society is increasing, and science education is a growing domain that gains international concern and becomes an important education for modern citizenship. However, a lack of students' interests of science and technology school subjects has been indicated by science educational research and international surveys (i.e. ROSE). For students, these subjects are considered to be abstract and irrelevant, and there is a decrease of the recruitment concerning scientific studies and careers in many industrialized countries. In contrast, no such phenomena have been discussed regarding public interest in science. These circumstances are pointed out by and have been given attention to by the ROSE (Relevance of Science Education) project, an international comparative project aiming to delineate learners perceived factors of importance to the learning of science (e.g. Jidesjö, Oscarsson, Karlsson, & Strömdahl, 2009). In addition to what is mentioned above, learning science can be demanding for students. Hence, it would be considered important to know how to teach science and to promote students' understanding and interests. Namely, teachers having good pedagogical content knowledge (PCK) in teaching science are of importance in science education.

Models play an important role when scientific knowledge is developed and when science is communicated, but the use of models in science education is not unproblematic. Students' difficulties in understanding models in general have been reported in research, and research has also shown that the use of models in science education can cause students to have learning difficulties (Grosslight, Unger, Jay & Smith, 1991; Ingham & Gilbert, 1991; Justi & Gilbert 2002a). Hence, the use of models in science can be a reason that makes students feel science is demanding and loose their interests in learning science. Moreover, when scientific knowledge is transformed into teachable school knowledge, actors as teachers and textbooks are included, according to the didactic transposition theory (Chevallard, 1989). The models are presented for students mainly through textbooks and teachers. It has been disclosed that textbooks' presentation influence the students' knowledge and understanding, as well as teachers' teaching (Sikorova, 2011; Tulip & Cook, 1993; Yager, 1983). In order to improve students' understanding, it is important for textbooks writers and teachers to become aware of the importance of how the models are presented, and which representations that might be a source causing students to have difficulties in understanding. The teaching will become more effective when teachers understand more about students' learning difficulties and the more representations and activities at their disposal (De Jong et.al, 2005). That is, it is important that teachers have good PCK of teaching science. In addition, to enhance teachers' PCK, it is necessary for teachers and textbook writers to get updated knowledge of research findings in science education (Justi & Gilbert, 2002b). Based upon the above mentioned importance of models and PCK, this thesis aims to investigate how models of chemical bonding are presented in school textbooks and by teachers in relation to the students' difficulties in understanding, and the teachers' teaching strategies in dealing with these difficulties.

In this thesis, chemical bonding is the concept chosen to conduct the study, since it is one of the most important topics taught in chemistry at upper secondary school level, and is also essential for other topics in chemistry (Nahum et al, 2008). This topic is dominated by the use of models (Taber & Coll, 2002), because we cannot see how atoms or other particles are held together (Coll & Treagust, 2003). During the past decade, research has shown that chemical bonding is a topic that students find difficult, and a wide range of students' difficulties in understanding are reported regarding this topic (e.g. Taber & Coll, 2002; Özmen, 2004). Accordingly, in this thesis, an analytical framework based on students' difficulties in understanding related to models in general and chemical bonding was developed to analyze the representations of models in textbooks and teachers' knowledge and teaching strategies. Moreover, whether textbook writers and teachers are aware of these learning difficulties in relation to models of chemical bonding is discussed.

In the following sections, I present the role and importance as well as problems of models in science and science education. The concept of PCK is also delineated. Since students' difficulties in understanding regarding models and chemical bonding models serves as a base for the development of the analytical framework used in the analysis in this thesis, research results about students' difficulties in understanding are described as well. Finally, the role of the textbooks is shown to remind us how important textbooks are.

Theoretical background

Models in science and science education

Models play an important and central role in science and science education in general as well as in chemistry and chemistry education, but the use of models in science education can be a source that makes students see science as a demanding and difficult subject. The role of models in each domain is described respectively as follows.

Models in science

The development of models is essential when knowledge is produced, and models have a wide range of functions in science (Gilbert, 2007). Scientists develop theories to explain the observed natural phenomena, and models in science are linked to the theories with phenomena and are part of these theories. Models can be used to make abstractions visible (Francoeur, 1997), or to provide the basis for predictions about and explanation of phenomena (Gilbert, Boulter, & Rutherford, 2000). A model can not only be seen as a description and/or simplification of a complex phenomenon (Gilbert, 2007), but also described as a proposal for how concepts, of which the world is believed to consist of, physically and temporally correlate to each other in the material world (Gilbert, Boulter & Elmer, 2000). Gericke and Hagberg (2007) define a model as a representation of a phenomenon initially produced for a specific purpose. Grosslight, Unger, Jay and Smith (1991) identified the nature of models, from interviews with experts, as entities that are actively created for a specific purpose, that is, to test ideas rather than as a copy of reality and noted that models might be changed in order to adapt new ideas. This view of models is used in the present study.

In chemistry, chemical ideas are presumed to have been visually, mathematically, or verbally modelled since they were first produced (Justi & Gilbert, 2002b). Models play a key role in the development of chemical knowledge (Gilbert, 2007). This key role started with the first concrete model of the atoms by John Dalton at the beginning of the nineteenth century. He was followed by several leading chemists who increased the use of models in chemistry, and today, several models are used when chemical knowledge about phenomena is produced and communicated (Justi & Gilbert, 2002b). Chemistry deals with the properties and transformations of materials which are essentially abstract, and there is a need for representations or models at sub-microscopic level to understand macroscopic observations (Oversby, 2000).

Models in science education

Using models is important when developing scientific knowledge, and models play an important role when science is communicated. The central role of models in science consequently gives them equal importance in science education, and models in science attain a wide variation of epistemological states (Gilbert, 2007). For example, a *mental model* is a private and a personal representation, created by an individual regarding, for instance, natural phenomena (Gilbert, 2007; Van Driel & Verloop, 1999). When a mental model is placed in the public domain and expressed through speech or writing, it can be called an *expressed model* (Gilbert, 2007; Gilbert et al, 1998). When scientists or researchers at the front line of science reach agreement about an expressed model, it can be termed a *scientific model*, it can be termed as a *scientific model,* for example, the Schrödinger model of the atom (Gilbert, 2007; Gilbert et al, 1998). When there is no easy correspondence between observational data and the scientific model, the model needs to be revised (Kuhn, 1996; Wimsatt, 1987). When the revised model replaces the earlier model, the earlier model is seen as a *historical model*. It often remains in use when there is a need to provide a base of explanation for a given purpose (Gilbert, 2007). Gilbert explains that in an educational setting, scientific and historical models are often modified into simplified versions and termed *curricular models*, and a *teaching model* is a model developed to support the learning of curricular models, often used in the form of analogies or metaphors. Attributes from separate historical models with different theoretical backgrounds can be transferred and merged into so-called *hybrid models* (Gilbert).

Problems regarding models in science education

In this thesis, two of the epistemological states of models mentioned above are of special interest: Hybrid models and teaching models. Hybrid models are often used by teachers and presented in textbooks in science education. Actually, a hybrid model then can be seen as a form of teaching model. The problem with hybrid models is that they might be difficult to use for teaching and learning (Justi & Gilbert, 2000). According to Taber and Coll (2002), a teaching model should be at an optimum level of simplification, that is, be kept as simple as possible while still being scientifically correct. In such a case, a teaching model provides a ground for students to develop later on in their learning process. If a hybrid model is used as a teaching model, it is not a suitable ground for developing more complex models at a higher educational level, because they are formed by attributes from *several* scientific models (that also can be historical models) that they will be meeting in the next level. The limitations of the models and that several models can be used to explain will then be unclear. It is quite obvious that this might be confusing for the students. The merging of attribute is probably made in order to make a teaching model less simplified, but the result might be a model which instead is difficult for the students to learn.

Teaching models in terms of simplified versions of scientific models developed for use in a teaching situation are frequently used in chemistry textbooks and by teachers. The need for simplifying the scientific models can be justified, but studies have shown that these teaching models failed both to support the students' understanding of a certain aspect of content and of the meaning of a model (Justi & Gilbert, 2002b). Moreover, the teaching models (hybrid models and/or simplified versions) can actually *cause* students to have learning difficulties, indicated by Gericke and Hagberg (2010b) in the context of genetics. They found that the models presented in textbooks were correlated to the alternative conceptions held by students.

There are further complications regarding models in science education. When the models are explained and expressed to the students, they can be expressed by the use of one or more of the five *modes of representation*, described as follows (Gilbert, 2007):

- The *concrete mode* is three-dimensional and made of resistant material, for example, a plastic ball-and-stick model of an ionic lattice
- The *verbal mode* can be either spoken or written, and can consist of 'a description of the entities and the relationship between them in a representation' (p.13), or an exploration of metaphors and analogies on which a model is based
- The *symbolic mode* can 'consist of chemical symbols and formula, chemical equations, and mathematical expressions' (p.13)
- The *visual mode* can be graphs, diagrams and animations, where two-dimensional representations of chemical structures are common examples
- The *gestural mode* consists of movements by the body or its parts.

But these circumstances are not the only problems. If the students have knowledge of different states of models and recognize their functions and limitations as well as the fact that a concept can be explained by several models, they gain a better understanding of scientific knowledge and nature of science (Boulter & Gilbert, 2000; Drechsler & Van Driel, 2008; Gericke & Hagberg, 2007). However, teachers and textbooks are not always explicit when using models (Drechsler & Schmidt, 2005; Gericke, Hagberg, Santos, Joaquim & El-Hani, 2012). Often the models are described as if the models themselves were the phenomena, and the models' nature and purpose are not discussed at all (Grosslight et al, 1991). Further, teachers might forget or they do not even know that they are communicating a model; instead, a model is presented as if it was a proven fact rather than a theory (Treagust et al., 2002).

In the studies involved in this thesis, the teaching models used by teachers and textbooks are investigated, with respect to the problems discussed in this section.

Models in the Swedish school curricula

The Swedish curricula regarding the science program and chemistry courses in upper secondary schools emphasize the importance of using models in teaching science. In this section I describe the Swedish curricula with respect to the use of models.

The curriculum for the non-compulsory school system contains the guidelines for upper secondary schools in Sweden (age 16-19). This curriculum states task, guidelines and goals for the schools. The curriculum valid when the studies included in this thesis were conducted were confirmed in the year 1994 (Swedish National Agency for Education, 2000/2006), although the curricula regarding program objectives and courses that each subject is taught in, were revised in the year 2000 (Swedish National Agency for Education, 2000/2003). Therefore, excerpts from these curricula regarding the use of models are described below.

The steering documents relating to these curricula exist on three levels:

1) National programmes; contains the specific educational objectives of each national program available for students to choose.
2) Aim of the subject; contains aims and goals to strive for in education of the subject, and describes the subjects' character.
3) Syllabus of the courses that the subject is taught in; specifies the aims and objectives of each course. These aims indicate the knowledge and skills students should have acquired on completion of the course. Further, the criteria for the grades are stated.

In the program objectives, the use of models is a crucial ingredient (Swedish National Agency for Education, 2000/2003a). It states:

> "*Acquisition of knowledge thus builds on the interaction between knowledge acquired through experience and theoretical models. Thinking in terms of models is central to all the natural sciences, as well as other scientific areas. The programme develops an understanding that we perceive scientific phenomena by means of models, often described in mathematical terms. These models are changed and enhanced by the emergence of new knowledge. A historical perspective contributes to illuminating developments that have taken place in the subjects covered by the programme and their importance to society.".*

This curriculum also states that the schools are responsible for ensuring that at the completion of the science program, students are able to:

"*Apply a scientific working approach based on problem solving methodologies, modeling, experiments and development of theory*" (Swedish National Agency for Education, 2000/2003a).

The importance of models is also listed in the aims of the subject regarding chemistry (Swedish National Agency for Education, 2000/2003b). It says that one of the objectives for chemistry education to strive for should be for the students to:

> *"develop their ability to […] describe, interpret, and explain chemical processes using natural scientific models"*

And furthermore to:

> *"Develop their ability, from chemical theories, models and own experiences, to reflect upon observations in their surroundings".*

In upper secondary schools, chemical bonding is a part of chemistry course A, the first one out of two levels (Swedish National Agency for Education, 2000/2003b). In Swedish textbooks and curriculum both inter and intra molecular forces are included as chemical bonding. The syllabus states that, on completion of the course, the students should have acquired skills to:

"be able to describe how models of different types of chemical bonding are based on the atoms' electron structure and be able to relate the properties of elements to type of bonding and its strength, as well as to the structure of the element"

The use of models is also emphasized in the grades for criteria. The level of proficiency that the student has achieved when the course is completed is assessed and awarded with a grade according to an ascending scale: Fail, Pass, Pass with distinction and Pass with special distinction. In the criteria for Pass for both courses in chemistry (Swedish National Agency for Education, 2000/2003b), following is required:

> *"Pupils use concepts, models and formulae to describe phenomena and chemical processes"*

The curricula for the non-compulsory school system in Sweden were revised in the year 2011 (Skolverket [Swedish National Agency for Education], 2011a). In these curricula (i.e. after the studies involved in this thesis were conducted), the use of models is even more emphasized. The main changes regarding the use of models are that the teaching of the nature of models is explicit emphasized in the aims of chemistry subject and the knowledge demands for the students regarding the nature of models are explicit specified in the grade for criteria, in both courses (Skolverket [Swedish National Agency for Education], 2011b). For instance, it is stated in the aims of chemistry subject (translated from Swedish):

> *"Chemistry is constantly developing in interaction between theory and experiment, where hypotheses, theories and models are tested, revalued and changed. Therefore, the chemistry education should discuss the development of theories and models, and their limitations and areas of validity".*

Further, it states that the education in chemistry should give the students the prerequisite to develop (translated from Swedish):

> *"Knowledge of chemistry concepts, models, theories and working approaches and understanding of their development"*

In the grades for criteria (Skolverket [Swedish National Agency for Education], 2011b), the students are required, in an ascending level according to each grade, to clarify for the meaning of the concepts, theories and working approaches of each topic of the course. The students are required to use them with ascending ability, and to be able to clarify, in an ascending level, how they are developed and to estimate the areas of validity and limitations of theories and models.

In sum, these excerpts show that the use of models is considered important and emphasized as a crucial ingredient in the curricula regarding the science program as well as in the syllabus of courses. In fact, the importance is increased in the up-to-date curricula.

Chemical bonding

Chemistry is dealing with the nature of substances and their transformations, which are essentially abstract (Justi & Gilbert, 2002).The nature of substances and the physical and chemical changes of substances are derived from the interactions between atoms or charged particles as ions, that is, chemical bonding (Coll & Treagust, 2003). Therefore, chemical bonding is one of the most central topics taught in chemistry at upper secondary school level, and is also essential for other topics in chemistry (Nahum et al, 2008). Students need to understand models for chemical bonding to understand chemistry, because we cannot see how atoms or other particles are held together. The chemical bonding models in focus in this thesis are the models of intra-molecular bonding (ionic, covalent and metallic bonding) not based on quantum mechanics. These bonds are the main type of chemical bonding, and in science literature and research in chemistry education, inter-molecular forces are not always considered as chemical bonding, but rather as inter-molecular forces. In the following sections, scientific models of these chemical bonds are described, according to university literature. Furthermore, the models based on quantum mechanics are briefly described, because attributes from these models are to be found in the teaching models (i.e. hybrid models) used by the textbooks and teachers involved in this thesis.

Scientific models of chemical bonding presented in University literature

In this section, scientific models of chemical bonding according to university literature are described. The literatures are in terms of university chemistry textbooks and chemistry work of reference, as chemistry handbooks, dictionaries and encyclopedia. These literatures are adapted to an education situation and therefore the models might be simplified to some extent, but likely less simplified than in chemistry textbooks for upper secondary level because the university literature are intended to be closer to the scientific models. The university literature will be the next level where the students are meeting chemical bonding models.

Chemical bonding in general

Chemical bonding in general is defined in several ways, for instance as: 'forces that hold atoms together in stable geometrical configuration' (Lagowski, 1997a, p.336); 'forces that hold atoms of elements together in a compound' (Silberberg, 2003, p.59); 'strong attractive force that holds together atoms in molecules and crystalline salts' (Parker, 1997); 'an attractive force between atoms strong enough to permit the combined aggregate to function as a unit' (Lewis, 2007). These forces between particles (e.g. atoms) arise from electrostatic attractions between opposite charges and are labelled chemical bonding (Silberberg, 2003).

The reasons for bonding to occur in general terms, are that bonding lower the potential energy between positive and negative particles, where the particles could be oppositely charges ions or atomic nuclei and the electrons between them (Silberberg, 2003), or that uncombined atoms are said to be not stable, and join together to form united atoms because of attraction between them, which forms chemical bonds (Henning & Hopp, 1983).

Forces between molecules, *inter-molecular forces*, are in some education research literature (e.g. Taber & Coll, 2002) included as chemical bonding, but in some university literature they are not included (e.g. Atkins, 1994; Hopp & Henning, 1983; Lagowski, 1997b; Lewis, 2007; Parker, 1997; Silberberg, 2003). For instance, they are called *non bonding forces*

(Silberberg). According to Silberberg, the forces breaking in chemical reaction are chemical bonding, bonding forces or intra-molecular forces, and influence the chemical properties of the substance, and inter-molecular forces influence the physical properties of the substance. According to Atkins, intermolecular forces are the forces responsible for holding molecules together, and affect the structure of solids and properties of liquids and real gases.

Ionic bonding

In the university chemistry literature, the transfer of electrons from a metal to a non-metal is central when ionic bonding is explained (Silberberg, 2003; Parker, 1997; Chang, 2005). Silberberg describe this transfer as a central idea and a solid is formed when the resulting ions attract each other strongly. Parker describe ionic bonding as a type of bonding in which one or more electrons are transferred, and Atkins (1994) define ionic bonding to be formed when one or more electrons are transferred from on atom to another. Chang define ionic bonding as the electrostatic force that holds ions together in ionic compound, but use reactions in terms of transfer of electron to introduce ionic bonding. In contrast, this transfer is not central according to Hopp and Henning (1983) and Lagowski (1997b) when ionic bonding is defined. Ionic bonding is defined as the result of electrostatic attraction between oppositely charged atoms or groups of atoms (Lagowski, 1997), or ions (Hopp & Henning). Lagowski later on says that the charged particles in ionic compounds are ions. Lewis (2007) defines ionic bonding as the result of electrostatic attraction between oppositely charged ions at one place, but refers to the transfer of electrons at another place. Atkins describe ionic bonding as one of the principal types of bond, in addition to covalent bonding, where the particles are hold together by Coulombic attraction between ions of opposite charge, and ionic bonding could be seen as 'a limiting case of a covalent bond between dissimilar atoms' (p.462).

The main-group element that forms monatomic ions are described to often attain filled outer levels, two or eight electrons, when forming monatomic ions, as the nearest noble gas (Silberberg, 2003). Ion formation requires energy, but a large amount of energy is released when the gaseous ions form a solid, called the lattice energy, also described as the enthalpy change when the gaseous ions form a solid (Silberberg). The lattice energy is also described as the energy required to overcome the attractive forces in an ionic compound (Lagowski, 1997b). The lattice energy depends on ionic size and charge, and can be calculated from the Born-Haber cycle (Silberberg; Chang, 2005; Lagowski).The importance of the lattice energy is pointed out by Chang and Lagowski when saying that the lattice energy determine the stability of the ionic compound, and by Silberberg: 'ionic solids exist only because the lattice energy drives the energetically unfavourable electron transfer' (p.333). Further, Lagowski points out that the stability is not determined by the electron configuration obtained when ions are formed.

The oppositely charged ions are held rigidly in position throughout the ionic lattice by strong electrostatic attractions (Silberberg, 2003; Lagowski, 1997b; Hopp & Henning, 1983). This ionic lattice explains the properties of ionic solids: hard, rigid, brittle, and conduct electricity when melted or dissolved in water but not in the solid state (Silberberg; Lagowski).

Covalent bonding

The covalent bonding model not based on quantum mechanics is described in terms of sharing of electron pairs by two atoms, explained by the American chemist G.N. Lewis in 1916, before quantum mechanics were established fully (Atkins, 1994). According to Lagowski (1997b), this model is simple but 'extremely reliable' (p.424). Covalent bonding was explained by Lewis as the sharing of electron pairs between two atomic centres, the electrons placed between them, with electrostatic force between the negative shared electrons and the positive nuclei (Lagowski). Chang (2005) describes that 'each electron in a shared pair is attracted to the nuclei of both atoms' (p.354), and this attraction is responsible for covalent bonds. The molecule became stable if the atoms in the molecule then had a complete octet of electrons, and the shared electron pair is described as 'the glue that bonds the atoms together by electrostatic interaction' (Lagowski, p.424). According to Silberberg (2003), covalent bonds occur when a shared pair of valence electrons attracts the nuclei of two atoms and hold them together, filling each atom's outer shell. This attraction draws the atoms closer, and repulsion between the atoms' nuclei and electrons also occur. The covalent bond results from the balance between these attractions and repulsion, where the system has its minimum energy (Silberberg). Covalent bonding is also defined as a bond in which two electrons are shared by two atoms (Atkins; Chang) or by two atomic nuclei or a pair of atoms (Lewis, 2007), or as a bond where 'each atom of a bound pair contributes one electron to form a pair of electron' (Parker, 1997). According to Hopp and Henning (1983) in a covalent bond, two atoms are hold together as a result of the atoms meeting and their electrons enter the 'attractive region', the electric force field of the positively charged nucleus outside the atom, of the other. The bonding is caused by the electrons between the nuclei, the region where the forces of attraction by the two nuclei are greatest, and where the electrons preferentially go (Hopp & Henning, 1983). That the electrons are localized in the region of the nucleus are also mentioned by Lewis (2007).

Polar covalent bonding

Polar covalent bonding is described in terms of covalent bonding with unequally sharing of electrons. This unequally sharing of electrons between the atoms emerges when atoms with different electro negativities form a bond (Silberberg, 2003; Lagowski, 1997c) resulting in partially negative and positive poles of the bond (Silberberg), or that the electron density is shifted toward the more electronegative atom (Lagowski). The unequal sharing is also described to occur when the electron pair is held more closely by one of the atoms (Parker, 1997) or the electrons lie nearer to one of the atoms in the bond, as a result of different attractive forces on the bonding electron pair (Hopp & Henning, 1983). Further reasons for the unequal sharing is that the electrons spend more time in the nearby region of one atom than the other, seen as a partial electron transfer or shift in electron density where the property electro negativity can be used to distinguish between non polar covalent bond and polar covalent bond (Chang, 2005).

Lewis (2007) does not use the term polar covalent bonds, instead covalent bonds are said to range from evenly shared electrons, non polar, to 'very unevenly shared', extremely polar. According to Atkins (1994), a covalent bond is non polar when the electron sharing is equal and polar when it is unequal.

Valence-shell electron-pair repulsion (VSEPR) theory, are used to construct the molecular shape from Lewis structure. 'Each group of valence electrons around a central atom is located as far away as possible from the others in order to minimize repulsion' (Silberberg, 2003, pp.370-371). A group is defined as any number of electrons that occupy a region around an atom, e.g. single, double or triple bound, or a lone pair. The three-dimensional arrangement of nuclei joined by the electron groups gives rise to the molecular shape.

A molecule with polar covalent bonds between the atoms and where the shape of the molecule leads to the molecule having a net imbalance of charge is called a polar molecule (Silberberg, 2003). According to Lagowski (1997c), polar covalent bonds impart to a molecule local densities of somewhat positive and negative charges of the molecule that 'contribute to the overall polarity or the dipole moment of the molecule' (p.1222). According to Chang (2005), a polar molecule is a molecule that has dipole moments, while Atkins (1994) define polar molecule as a molecule with permanent electric dipole moment.

Metallic bonding

Metallic bonding is explained in terms of the electron-sea model (Silberberg, 2003; Parker, 1997). In this model, the metallic lattice is described to consist of the atomic cores, seen as cations, surrounded by the metal atoms' delocalized valence electrons that form an 'electron sea'(Silberberg), or immersed in a sea of delocalized electrons (Chang, 2005). The electrons attract the metal cations together (Chang; Silberberg). There also exists models for metallic bonds in terms of electron-sea but without the term delocalized electrons and lack of the bond due to the attraction between cores and electrons. The metallic bond is then seen as the result of the sea of electrons free to move throughout the metallic lattice (Parker). These valence electrons, free to move between the atomic cores, are also said to form a so-called electron gas, that ‘glue’ the cations of the metallic lattice together, that is, the metallic bonding (Hopp & Henning, 1983). Some literature do not use the term electron-sea, but similar to Silberberg, the metallic bonds are seen as the attraction between the atomic nuclei and the ‘outer shell electrons’ which are shared ‘in a delocalized manner’ (Lewis, 2007, p.172). In some university literature (Atkins, 1994), the metallic bond is only explained with the band theory according to molecular orbital (MO) theory (explained below). Lagowski (2007c) use a model for metallic bonding in terms of ‘band of orbitals’ with very small energy separations delocalized over the entire crystal.

Models based on quantum mechanics

Two models for covalent bonding that are based on quantum mechanics are valence bond (VB) theory and molecular orbital (MO) theory. Ionic bonding can be captured by the MO theory as a special case of covalent bonding and metallic bonding can also be explained by a model based on MO theory, the band theory.

VB theory says that ‘a covalent bond forms when the orbitals of two atoms overlap and are occupied by a pair of electrons that have the highest probability of being located between the nuclei’ (Silberberg, 2003, p.393). When this orbitals overlap in the molecule, new atomic orbitals are created that are different from the orbitals in the separated atoms. This orbital mixing is called hybridization, and the new atomic orbitals are called hybrid orbitals (Silberberg, 2003; Chang, 2005; Atkins, 1994). The VB theory describes ‘each electron pair in a molecule by a wave function that allows each electron to be found on both atoms joined by the bond’ (Atkins, p.463). According to Lagowski (1997a), each bonding pair of electrons has its own wave function ‘belonging to a particular pair of atomic nuclei localized in one part of the molecule’ (p.337). The spatial orientation of each type of hybrid orbital corresponds with the electron-group arrangement predicted by VSEPR theory (Silberberg).

According to the ***MO theory***, a molecule can be described as a collection of nuclei with the electron orbitals delocalized over the entire molecule

(Silberberg, 2003), or the electrons should be regarded as spreading throughout the entire molecule, instead of belonging to a particular bond (Atkins, 1994). In the same way that an atom has atomic orbitals, a molecule has molecular orbitals, resulting from interaction of the atomic orbitals, which have a given energy and shape (Atkins; Chang, 2005; Silberberg). These molecular orbitals are said to be: occupied by the molecule's electrons (Silberberg); spreads throughout the molecule (Atkins); associated with the entire molecule (Chang); belonging to the whole nuclear framework of the molecule (Lagowski, 1997c). According to Lagowski, the covalent bonding is a quantum effect associated with an increased mobility of the electrons, which are able to move around and between the two nuclei, because of bond formation.

Metallic bonding can be explained according to ***the band theory***, an extension of the MO theory (Silberberg, 2003). The band theory can be described as overlap between the atoms' orbitals when atoms after atoms lies in a three-dimensional array, forming molecular orbitals (Atkins, 1994), or as explained by Chang (2005), 'delocalized electrons move freely through 'bands' formed by overlapping molecular orbitals' (p.852). The orbital energies are so close together that they form a continuous band of molecular orbitals (Silberberg).

Teachers' knowledge

What types of knowledge is needed to be a 'good' teacher? A commonly used argument in the international debate is that the better subject matter knowledge a science teacher possesses, the better a teacher can teach the subject (Kind, 2009). But possession of good subject matter knowledge does not necessarily guarantee that someone will be good at teaching the specific subject. A teacher also needs to possess effective teaching skills (Kind, 2009). As commented by Bucat (2004):

"There is a vast difference between knowing about a topic, and knowing about the particular teaching and learning demands of that particular topic" (p.217).

Clearly, more than one type of knowledge is needed, and one can talk about a practical knowledge base characteristic for a science teacher. In the literature regarding teachers' knowledge, a wide range of words are used to describe the knowledge needed for teaching (Nilsson, 2008a). For instance, craft knowledge, tacit knowledge, situated knowledge, professional knowledge, personal knowledge, pedagogical content knowledge (PCK) or pedagogical context knowledge. Even if different *names* are used, they might not necessarily refer to different *types* of knowledge, therefore the focus would be on the meaning of the concept (Nilsson).

In this thesis, I will concentrate on the concept of PCK. This concept has attracted much attention since it was introduced by Shulman in 1986. PCK can be said to represent the knowledge used by teachers in the process of teaching (Kind, 2009), or as the knowledge of the teaching and learning of a particular subject matter where the learning demands essential in the subject matter is considered (Bucat, 2004). As an academic structure of teachers' knowledge, PCK has become a way of understanding the complex relationship between teaching and content through the use of specific teaching approaches (Van Driel et al., 1998). Why PCK can be considered important and useful, the exploration of the concept and how PCK develops will be discussed in the following sections.

Why is PCK important in science education?

PCK is indeed a complex concept, and it is not unproblematic to get experienced teachers to express their practices or to follow the development of a pre-service teacher's PCK (Kind, 2009). But there is strong evidence that PCK offers a useful concept and tool for describing and to help us understand teachers' unique professional practices. The concept of PCK provides a theoretical as well as a methodological framework for understanding and examining teachers' skills, and to structure research on teachers' knowledge and how it is developed (Abel, 2008; Nilsson, 2008a). The concept of PCK can offer answers to how teachers should use the content (i.e. knowledge of concrete models and teaching strategies) of the particular subject in order to promote students' understanding.

The origins of PCK

In order to fill in the gap in understanding how teachers' subject matter was transformed into teachers' instructions and to evaluate teachers' competences, Shulman (1986) proposed three categories of teachers' knowledge: subject-matter content knowledge, subject-matter pedagogical knowledge, and curricular knowledge. Shulman argued that teachers need a special type of knowledge to structure the content of their lessons and then to use specific representations or analogies in order to promote students' understandings. These first three categories were then refined into seven (Shulman, 1987):

- content knowledge
- general pedagogical knowledge
- curriculum knowledge
- pedagogical content knowledge
- knowledge of learners
- knowledge of educational context
- knowledge of educational purposes

The concept of PCK was one on these components, defined as "that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding" (Shulman, 1987, p.8).

Shulman saw PCK as content knowledge transformed by the teacher into a form that makes it understandable to students. Shulman argued that PCK was a type of knowledge unique and distinctive for teachers. The other types of knowledge have their equivalents in different fields. For instance, in medicine, the curriculum knowledge consists of, among others, knowledge of anatomy, medicine or surgical procedures, and knowledge of learners comprises, for instance, the attention that patients require.

The proposal of the concept of PCK in 1986 and 1987 served the purpose of introducing 'teacher knowledge' as a general concept and PCK as one of the components of this knowledge (Kind, 2009). Shulman's key components of PCK were a) knowledge of instructional strategies (in the beginning labeled 'representations') and b) knowledge of students' specific learning difficulties (Kind). Shulman described PCK as the teachers' knowledge of how to represent and formulate the specific subject that makes it comprehensible to the students. In PCK, teachers' understanding of a topic is combined with instructional strategies and additional knowledge. Since Shulman's introduction of PCK, the concept has attracted much attention, and has been further developed by numerous science educators. But there is no consensus in the definition or conceptualization of the concept, and many models of PCK have been proposed (reviewed by e.g. Abell, 2007; Gess-Newsome, 1999; Kind, 2009), described in the following section.

The exploration of models of PCK

The models of PCK can be described with respect to the fact that if the knowledge bases which construct PCK are integrated (integrative models) or transformed (transformative models). These knowledge bases are subject-matter knowledge (SMK), pedagogical knowledge (PK), and contextual knowledge (CK). The SMK refers to a teacher's quantity, quality, and organization of information, conceptualizations, and underlying constructs in a given field (of science) (Zeidler, 2002). PK refers to the understanding of teaching and learning processes independent of subject matter (Bucat, 2004), and the CK is strongly connected to PK and represents knowledge of school departments, traditions, behaviour of students, the atmosphere in the classroom, the relationship between individuals, and the context in which teaching takes place (Nilsson, 2008a). The integrative and transformative models were proposed by Gess-Newsome (1999) as a way of describing PCK as a continuum of models, with the integrative model at one extreme (Figure 1, left), and the transformative model at the other extreme (Figure 1, right). In the *integrative model*, teacher knowledge is explained as an intersection of subject matter, pedagogy and context, and these domains are seen as independent knowledge bases. PCK does not exist as a separate knowledge component, and SMK is an integral part of PCK. When the teacher is teaching in the classroom, knowledge from all the three domains is integrated in order to create effective learning opportunities. Gess-Newsome here uses the simile of a chemical mixture: the components are indistinguishable at macroscopic level but the identities are retained. In the *transformative model*, knowledge of subject matter, pedagogy and context are transformed into a new form of knowledge, PCK. It can be seen as a synthesis of all knowledge needed in order to be an effective teacher. SMK is a separate component, changed when PCK is developed. The transformative model can be likened to a chemical compound: the components are rearranged, forming something new, and cannot easily be separated.

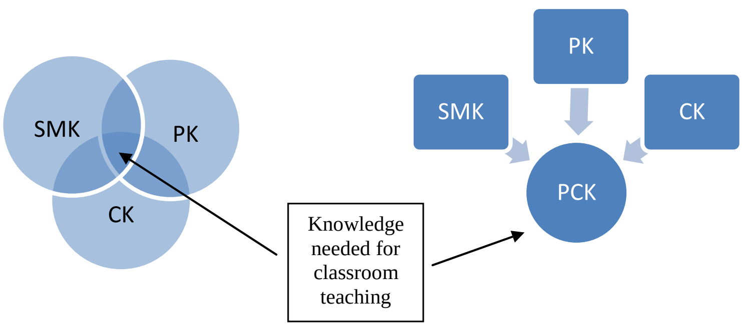


Figure 1. The integrative (left) and transformative (right) models of teacher knowledge (in accordance to Gess-Newsome, 1999)

The most common position is somewhere between these two extremes (Gess-Newsome, 1999). It is also suggested that integrative and transformative PCK can be used by the same teacher but at different times, depending on classroom events (Appleton, 2005). Seen in this way, there will be places for both these models of PCK in the overall picture. If one makes a parallel to what I have been discussing in previous sections regarding models in science, that different models can be used to explain the same phenomena, I think this view of PCK might seem to be reasonable, because PCK is a model of teachers' special practice knowledge.

The models of PCK can also be described with respect to how the models combine Shulman's original seven components of teachers' knowledge *within* PCK in different ways, sometimes different names of the components are used, but with the same meaning (Kind, 2009). Besides, three new components are proposed: assessment, socio-cultural issues, and school knowledge (Kind). Grossman's model of PCK (1990) consisted of four components: knowledge of the purpose for teaching specific subject matter, knowledge of students' understanding and conceptions, knowledge of curriculum, and knowledge of instructional strategies. Magnusson and co-authors (1999) addressed that the concept of PCK is consisted by five types of knowledge: orientations towards science teaching, knowledge of the curriculum, knowledge of assessment, knowledge of science learners, and knowledge of instructional strategies. Loughran and his colleagues (2001) have defined PCK as "the knowledge that a teacher uses to provide teaching situations that help learners make sense of particular science content" (p. 289).

There also exist models of PCK where SMK is included within PCK. For instance, Marks' model (1990), based on research evidence, consists of the four components: SMK, instructional strategies (re-named 'instructional processes'), students' learning difficulties (re-named students' understanding'), curricular knowledge (re-named 'media for instruction'). A further example based on research evidence is the model proposed by Fernández-Balboa and Stiehl (1995) that consists of: SMK, knowledge of students, instructional strategies, the teaching contexts and teaching purpose.

According to Kind (2009), among the different models of PCK described above, Shulman's proposal, Grossman (1990) and Magnusson et al. (1999) can be seen as transformative, and SMK is then a separate knowledge-base. The remaining models are seen as integrative, and do not separate SMK from PCK. Regarding the SMK, the difference between science and school science is argued (Gericke, 2008; Kind & Taber, 2005). If this is applied to PCK, as a teacher gains experience, the SMK may be used differently and develop different characteristics. Further, SMK might be more difficult to distinguish as a separated component in experienced teachers' PCK (Kind, 2009).

To summarize, concluding all the above-mentioned PCK models, it can be found having two main components: (1) knowledge of students' learning difficulties (also called, e.g. students' understanding, knowledge of students, and knowledge of science learners) and (2) instructional strategies within PCK. In this thesis, in accordance to De Jong, Van Driel and Verloop (2005), the first component is concerned in relation to students learning a specific topic and comprises knowledge of students' learning difficulties. The learning difficulties in focus in this thesis are alternative conceptions and difficulties in understanding. The second component, knowledge of instructional strategies, includes knowledge of specific representations, and specific teaching activities (e.g., experiments). According to De Jong et al. (2005), teachers' knowledge about specific conceptions and learning difficulties, and representations and teaching strategies, are essential in all research that concerns teachers' knowledge. They claim that the teaching of a certain topic became more effectively the better teachers understand students' learning difficulties and the more representations and activities they have at their disposal. The importance of the knowledge of students' learning difficulties (alternative conceptions and difficulties in understanding) is also pointed out by Taber (1995), who reported that alternative conceptions held by the students had repercussions for the understanding of related concepts, and may block effective learning.

Development of PCK

To date, there has been a lot of research aiming at identifying the concept of PCK. Nilsson (2008a) stresses that, at this point, instead of arguing about the definition of PCK, it is important to focus on the processes that are involved in the development of PCK. In Grossman's model (1990), PCK is seen as developed as a result of a knowledge transformation, with a reciprocal relationship between the domains. Magnusson et al. (1999) see the development of PCK as a complex process determined by the content to be taught, the context in which the content is taught and the way the teacher reflects on his/her teaching experiences. In addition, reflection as crucial to develop PCK has been addressed by several researchers. When

Drechsler and Van Driel (2008) investigated experienced teachers' PCK of teaching acid and bases, all teachers in their study mentioned, by reflecting on students' difficulties, was a reason to change how they taught the topic. Nilsson (2008b) concluded that reflection on teaching practice experiences is crucial when pre-service teachers develop their PCK. If pre-service teachers are encouraged to share their experience and to interpret, value and learn through reflection, these experiences can contribute to development of PCK (Nilsson, 2009). The development of PCK as an integrated process rooted in classroom practice has been pointed out by Van Driel et al (1998). The importance of teaching experience is also expressed by the following: "PCK is the knowledge that teachers develop over time, and through experience, about how to teach a particular content in particular ways in order to enhance students learning" (Loughran, Mulhall & Berry, 2006, p. 9). In sum, it is of importance for us, educators as well as researchers, to put effort and investigate into the development of PCK in our teacher education to benefit teaching and learning.

Students' difficulties in understanding

As discussed in previous sections, the use of models is central and important in science education, but can also be a reason for students to see science as a demanding and difficult subject. Regarding models in general, to date, there are several research reports about students' difficulties in understanding. Regarding models of chemical bonding, considerable research findings reported over the past decade establish chemical bonding as a topic that students find difficult (Özmen, 2004; Taber & Coll, 2002). In this section, I give examples of students' difficulties in understanding and possible sources according to research literature, for models in general and models of chemical bonding in particular. I also describe some altered frameworks for presenting chemical bonding. Finally, I present the framework used to analyse the representations of models of chemical bonding analysed in the studies involved in this thesis.

Models in general

Regarding models in general, some students regard models as an exact replica of the real thing (Grosslight et al, 1991; Ingham & Gilbert, 1991), and have a tendency to transfer macroscopic properties to particles. The latter is suggested to depend on the fact that the nature and role of models are not clearly understood (Othman, Treagust, & Chandrasegaran, 2008; Taber, 2001). As mentioned in the section regarding models in science education, it is common that the nature and purpose of the models are not discussed and teachers and textbooks are not always explicit when using models (e.g. Drechsler & Van Driel, 2008; Gericke et al, 2012). Further, the teaching models used in science education (hybrid models and/or simplified versions) can cause students to have difficulties in understanding (Gericke & Hagberg, 2010b). Especially hybrid models might be confusing for the students and difficult to learn (e.g. Justi & Gilbert, 2000).

Models of chemical bonding

Taber and Coll (2002) claimed that due to the way chemical bonding is taught, students over-generalise the limited teaching model 'the octet rule', and develop a common alternative conceptual framework, labeled the *octet framework.* This framework then influences the students' thoughts about bonding. Factors in the way chemical bonding is taught that can be seen as sources of developing the octet frame work are: use of the octet rule and focus on electronic configurations, a focus on separate atoms, lack of reason for why bonding occurs, anthropomorphic descriptions of chemical processes, and not pointing out that chemical bond is due to electrostatic forces (Taber & Coll, 2002). The authors argued that if there is *a lack of discussion of why chemical reactions occur,* it leads to an 'explanatory vacuum' (p.217), and if the *octet rule and focus on electronic configuration* are used to present chemical bonding, the octet rule will be a feasible alternative explanation for why bonding occur. The fecundity of the octet rule depends on the students' conception that everything derives from and comprises of atoms. Therefore, a *focus on separate atoms* regarding chemical reactions can be seen as a source for students to develop the octet frame work (Taber & Coll). Anthropomorphic descriptions of chemical processes might be the source for students to think that atoms have needs or wishes, a contribution to the development of the octet framework. Further, if *anthropomorphic explanations* are used habitually, they could shift from standing-in into taking the place of the explanation. Hence, students may not see a reason to develop more sophisticated explanations (Taber & Coll, 2002; Taber & Watts, 1996).

The octet framework can lead to the overall idea that students expect atoms wanting to have 'octets' or a 'full outer shell', and this is the reason for chemical processes to occur (Taber & Coll, 2002). The students then maintain an incorrect and inappropriate reason for why bonding occurs. For chemical bonding in general, research reports that it is common for students to use the right concept but wrong explanation and students are not able to provide a correct explanation for bonding phenomena and why bonding occurs (Nicoll, 2001). The source of this might be the absence of discussing the reason for why bonding occurs (Taber & Coll, 2002).

Additional sources of students' learning difficulties are proposed in the literature. For instance, if ionic bond is presented in terms of *electron transfer*, together with not presenting chemical bonding due to electrostatic forces, it could lead to the conception that ionic bonding is identified with electron transfer instead of electrostatic forces. Further, that ionic compound contains molecules and ionic bonds only exist between ions which had transferred electrons (Taber & Coll, 2002). The teaching model of covalent bonding as pairs of electrons shared by two atoms is the most common model used to explain covalent bonding. If covalent bonds are presented in terms of: *electron sharing*, the octet rule, anthropomorphic descriptions and are *not* presented as due to electrostatic forces, it might give the students the alternative conception that the shared electron pair in itself *is* the bond and the electron pair hold the atoms together *because* they then receive a noble gas shell (Taber & Coll). Students commonly have difficulties to proceed further from the idea of the shared electron pair, which does not provide for progression (Taber, 2001; Taber & Watts, 2000). Presenting ionic and covalent bonding in terms of electron transfer and electron sharing in addition to the octet framework, possibly results in students discounting from bonding anything which does not fit the description of 'electron sharing' or 'electron transfer' (Taber & Coll, 2002).

Regarding the concept of polar covalent bonding, Harrison and Treagust (1996) indicated that the bond polarity, shape of molecules and polarity of molecules are unclear to the students. The reason for this, according to Taber and Coll (2002) could be confusion over the understanding of electro negativity and *presenting ionic and covalent bond as a dichotomy*. The authors also suggested the latter as the reason for the fact that students tend to see bond polarity as a characteristic of the covalent bond instead of something *in between* ionic and covalent bonds.

There are several research findings concerning the students' difficulties in appreciating lattice structure, which does *not* consist of molecules, for instance, ionic compounds, giant covalent lattice and metals. One source of this could be if these *bonded non-molecular materials are presented as involving discrete molecules*. And regarding metallic lattice, if the students are very influenced by the term 'sea of electrons' used in the scientific model of metallic bonding which is not based on quantum mechanics, they might conceptualize this sea as a vast excess of electrons, that actually would be charged and unstable (Taber, 2001). Another important factor is the *order of introducing the types of bonding*. Teaching covalent bonding before ionic bonding is a common practice which could make students see ionic lattice as containing molecules, and moreover, students see all bonded materials as involving molecules (Taber & Coll).

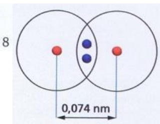
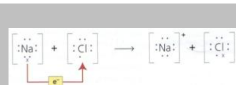
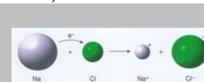
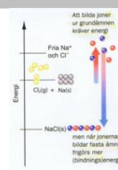
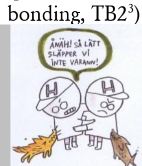
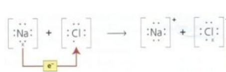
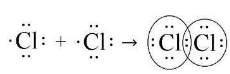
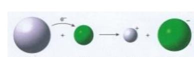
Altered frameworks and teaching models

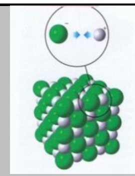
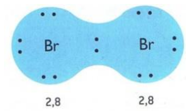
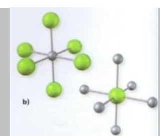
There are some altered frameworks suggested to teach chemical bonding, that is, a main change in character of how chemical bonding is presented. One altered framework suggested is to use the ionic, metallic and molecular lattice as the point of origin, and physical principles as the focal points, avoiding emphasis of atoms and bonding introduced as an electrical concept (Taber, 2001; Taber & Coll, 2002). A teaching model for chemical bonding based upon the effect of electrostatic forces will be, according to Taber and Coll (2002) at an optimal level of simplification that provides a ground for students for more sophisticated chemical bonding models based on quantum mechanics at university chemistry level. To avoid the students to apply the 'molecule presence' to all structure, the authors suggest teaching metallic bonding first, followed by ionic bonding , and covalent bonding last, and in the context of covalent bonding to start with giant covalent lattice before discrete covalent molecules. Nahum and colleagues (2008) suggested the 'bottom-up framework', where chemical bonding is introduced as a continuum of related concepts instead of different types of bonding, with an emphasis on electrostatic interactions, stability and focus on the nature of the chemical bond.

Analytical framework to analyze representations of models of chemical bonding

To analyze the representations of chemical bonding in the studies involved in this thesis, an analytical framework based on the students' learning difficulties regarding models in general and models of chemical bonding was developed from the data together with the research literature. Categories on to nine were divided in three modes of representation: verbal, symbolic, and visual modes (Gilbert, 2007). The categories are presented in Table 1. Regarding category six, seven, and nine, the headings of these categories are not by themselves a source of students' learning difficulties: Actually *lack of* or *inappropriate* reason for why bonding occurs, *not* presenting chemical bonding as due to electrostatic forces and *not* explaining the model's nature and purpose might be sources.

Table 1. Categories used to identify representations that might cause students to have learning difficulties, including examples from textbooks and teachers of each category and the modes of representation respectively.

The categories	**The modes of representation**		
	Verbal mode	**Symbolic mode**	**Visual mode**
1. Use of octet rule and focus on electronic configurations	'all ions formed have attained noble gas structure, i.e. they fulfil the octet rule' (Ionic bonding, TB4, pp.137).	$Na + Cl \rightarrow Na^+ + Cl^-$ 2 8 1 2 8 7 2 8 0 2 8 8 (ionic bonding, TB5)	 (covalent bonding, TB2[1]).
2. Focus on separate atoms when representing chemical reactions	'each sodium atom donate one electron and each chlorine atom accept one electron' (ionic bonding, TB4, pp.137)	 (ionic bonding, TB1)	 (ionic bonding, TB3[2])
3. Reason for why bonding occurs a. octet rule b. energy changes	*'One talk about to achieve noble gas structure, that is some kind of driving force'* (T2)	 (covalent bonding, TB2)	 (polar covalent bonding, TB2[3])
4. Anthropomor-phism and chemical processes	*That they [atoms], want to be pleased, sort of, we use that often.* (T8)	None	 covalent bonding, TB2[4])
5. Chemical bonding presented in terms of *a. electron transfer* b. *electron sharing*	'Ionic bonding: Electrons are donated by one atom and accepted by another' (electron transfer, ionic bonding,TB4, pp.140) 'a covalent bond where the electrons are not shared equally between the bonded atoms is called polar covalent bonding' (electron sharing, polar covalent bonding, TB1,	 (electron transfer, ionic bonding, TB1)  (electron sharing, covalent bonding, TB1)	 (ionic bonding, electron transfer, TB1[4])

6. Chemical bond due to electrostatic forces	*'The attraction between plus and minus ions give the very bonding'* (T8)	None	 (ionic bonding, TB3[5])
7. Attribute from different historical models merged to hybrid models	Two electrons form a pair, ***communally for both atoms*** (*electron sharing*), and then ***surrounded by the same electron cloud*** (quantum mechanical model of atom, QMA) ***as a noble gas*** (*octet rule, OF*). For hydrogen, one can do good ***calculations of how the electrons behave*** *(QMA)*, and then get a picture of the ***density of the electron cloud*** (molecule orbital theory, *MO*). (covalent bonding, TB5, pp.150)	None	 (covalent bonding, TB4[6])
8. Bonded non-molecular materials presented as involving discrete molecules	'the ion pair Na$^+$Cl$^-$ is the crystal's smallest 'building element'. (ionic bonding, TB2, pp.57)	$2Na + Cl_2 \rightarrow 2Na^+Cl^-$ (Ionic bonding, TB1)	 (Ionic bonding, TB2[7])
9. Explaining nature and purpose of models	'The models used here is strongly simplified, but yet useful' (TB4)	None	None
10. Order of introducing types of bonding	1. Ionic bonding, 2. covalent bonding, 3. polar covalent bonding, and 4. Metallic bonding (TB1, TB3 and TB4; T1, T2-T5, T6, T8, and T9)		
11. Use of typical examples	Sodium chloride (ionic bonding, all textbooks and teachers)		

[1] From "*Gymnasiekemi A*", by S. Andersson, A. Sonesson, O. Svahn and A. Tullberg, 2007, p.70. Reprinted with permission of Cicci Lorentzson (illustrator).

[2] From "*Kemiboken*", by H. Borén, A. Boström, M. Börner, M. Larsson, S. Lillieborg and B. Lindh, 2005, p.91. Reprinted with permission of Per Werner Shulze (illustrator).

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[5] From "*Kemiboken*", by H. Borén, A. Boström, M. Börner, M. Larsson, S. Lillieborg and B. Lindh, 2005, p.92. Reprinted with permission of Per Werner Shulze (illustrator).

[6]From *"Kemi A: Tema & Teori"*, by C. Engström, P. Backlund, R. Berger, and H. Grennberg, 2005, p. 140. Illustrator: T. Widlund. Reprinted with permission of the publisher.

[7] From "*Gymnasiekemi A*", by S. Andersson, A. Sonesson, O. Svahn and A. Tullberg, 2007, p.57. Reprinted with permission of Per Werner Shulze (illustrator).

The role of textbooks

Teachers and textbooks are included in the didactic transformation where scientific knowledge is transformed into teachable school knowledge (Chevallard, 1989). In previous sections, I have described the role and problems of models in science education, the teachers' knowledge of teaching and students' learning difficulties. Finally, in this section, I will describe the role of school textbooks. The placement of this section has nothing to do with ranking the importance. Textbooks are as important as teachers in the process of students' learning and textbooks have a broad variety of functions and are used intensively in schools (Mikk, 2000)

In the perspective of the students, textbooks have a unique role as obligatory reading material (Ekvall, 2001), and to represent information (Mikk, 2000). The latter is one of the most important functions of a textbook and one of the main characteristics then is scientific correctness (Mikk, 2000). From a teacher's perspective, textbooks are used as a source for the content and as a programme for teaching (Sikorova, 2011), that is, the textbooks are used to prepare science lessons and as a starting point for new topics (Peacock & Gates, 2000). Other purposes for teachers to use textbooks are to search for information about subject matter, for instance, how it is structured, if presented in detail or not, and the sequence of topics (Sikorova, 2011). In the context of pre-service teachers, the role of textbooks as a curriculum guide has been reported (Nicol & Crespo, 2006). The role of textbook as the most thorough representation of curricula is also pointed out by Mikk (2000).

Regarding the role of textbooks in teaching and learning of models, there are several research findings indicating problems. For instance, the use of hybrid models was found in the context of chemical kinetics and models of atoms (Justi & Gilbert, 2002b), and for describing phenomena in the context of genetics in six different countries (Gericke & Hagberg, 2010a; Gericke et.al, 2012). Further, teaching models are frequently used in chemistry textbooks, and studies have shown that these teaching models failed both to support the students' understanding of a certain aspect of content and of the meaning of a model (Justi & Gilbert, 2002b). It is also indicated that, in the context of genetics, the models presented in the textbooks can cause students to have learning difficulties (Gericke & Hagberg, 2010b). The authors found that the models presented in textbooks were correlated to the alternative conceptions held by students. These findings show that it is important for the teachers as well as the textbook writers to be aware of both the way of *how* the models are presented in textbooks and *what* teaching models they use might influence the students' understanding.

As mentioned above, textbooks have a tremendous influence on teachers' teaching and students' learning. Consequently, it is important to evaluate textbooks in order to find out their shortcomings; otherwise, the textbooks will change slowly, and scientific research can improve the development of new and better textbooks (Mikk, 2000). That the importance of analyzing textbooks is crucial is also pointed out by Justi and Gilbert (2002b), with respect to that in chemical education, the textbook is the most widely and frequently used teaching aid. In line with this, the analysis of textbooks was in focus in the study reported in Paper 1. Here, the models of chemical bonding presented in school textbooks, based on the afore-mentioned research literature regarding students' learning difficulties, were analyzed. In the study reported in Paper 2, one of the aims was to investigate the influence of the textbooks on the teachers' selection of how the models are represented.

Aims and research questions

The overall aim of this research was to investigate how models of chemical bonding are presented in school textbooks and by teachers in relation to the students' difficulties in understanding. For these investigations, I aimed to develop an analytical framework in order to analyze the representations of models of chemical bonding. This framework was based on research literature about students' difficulties in understanding regarding models in general and chemical bonding in particular, together with data from the studies. Regarding the study concerning how the teachers presented the models, the aim was to investigate the teachers' PCK of teaching chemical bonding in order to promote students' understanding. The focus was on the teachers' knowledge of students' learning difficulties and teaching strategies to meet these difficulties. The knowledge of students' difficulties in understanding also includes alternative conceptions. Knowledge of teaching strategies includes knowledge of specific representations and specific teaching activities.

The specific research questions were:

Paper 1:

- To what extent can representations of chemical bonding in different chemistry textbooks be identified that are relevant from the perspective of students' difficulties in understanding chemical bonding?
- In what ways might the representations of models of chemical bonding cause students to have difficulties in understanding?

Paper 2:

- What is the teachers' knowledge of students' alternative conceptions and difficulties in understanding chemical bonding?
- What teaching strategies that take students' difficulties in understanding chemical bonding into account are reported by the teachers?
- What ways of textbooks' influence on the teachers' selection of how models of chemical bonding are represented can be identified?

Methods

In this study, to analyze the textbooks, a content analysis was used. The Lesson Preparation Method (Van der Valk & Broekman, 1999), consisting of teachers prepared lesson plans and individual interviews with the teachers, was the main approach used to analyze the teachers' PCK of teaching chemical bonding in order to promote students' understanding. In the following section, the textbooks, participating teachers and research design are presented.

School Textbooks

The chapters concerning chemical bonding in five chemistry textbooks, from different publishers at upper secondary level in Sweden (student's age from 16 to 19) were analyzed. These textbooks were used by the teachers involved in the overall study of this thesis. The school textbooks are indicated as TB1-TB5. The textbooks belong to the most widely used chemistry textbooks (all but one, TB4).

Participating teachers

Thirteen chemistry teachers at seven upper secondary schools, located in Central Sweden, were contacted. Ten of the contacted teachers volunteered to participate in the project. In this thesis, they will be referred to as T1-T10. The teachers T3-T4 were colleagues at the same school, and T5-T7 taught at one of the other schools. The other teachers worked at different schools. More information about the teachers is given in Table 1.

Table 1. Information about the participating teachers, indicated as T1-T10. The textbooks used by the teachers are indicated as TB1-TB5.

Teacher	Gender	Years of teaching experience		Textbook used by the teacher	Teaching subject beside chemistry
		Total	*Chemistry in upper secondary school*		
T1	Male	36	10	TB3. Borén et al, (2005)	Mathematics
T2	Male	10	5	TB5. Pilström et al, (2007)	Biology
T3	Male	10	10	TB5. Pilström et al (2007)	Mathematics
T4	Male	35	20	TB5. Pilström et al (2007)	Biology
T5	Female	15	15	TB3. Borén et al (2005)	Biology
T6	Male	7	7	TB3. Borén et al (2005)	Biology
T7	Female	>30	30	TB3. Borén et al (2005)	Mathematics
T8	Female	5	5	TB4. Engström et al, (2005)	Science
T9	Male	19	10	TB1. Andersson et al, (2000)	Biology Science
T10	Female	3	3	TB2. Andersson et al, (2007)	Mathematics

Research design

This study was designed as a small-scaled explorative study, and consisted of four main steps (Figure 2): step 1, a preliminary analysis of the chemistry textbooks, used by the teachers when teaching chemical bonding; step 2, a preliminary analysis of lesson plans about chemical bonding that was individually prepared by the teachers; step 3, based on step 1 and 2, semi-structured interviews with the chemistry teachers about their lesson plans and teaching; step 4, depth analysis, a second round analysis of the textbooks, lesson plans and interviews. The depth analysis of the textbooks (in step 4) is reported in Paper 1 as a separate part of the whole study. The preliminary analysis of the textbooks and the teachers' lesson plans (step 1 and 2) were conducted to prepare specific questions for the interviews with the teachers.

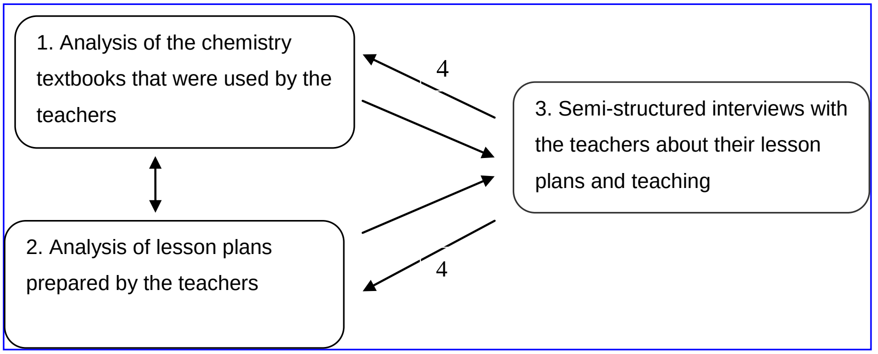

Figure 2. The four main steps of the study

The Lesson Preparation Method (Van der Valk & Broekman, 1999) usually consists of two main parts: a) the lessons preparation task, and, b) the individual interview. In this study, regarding the lesson preparation task, the teachers were asked individually to prepare and send their lessons plans 1-2 weeks before the interview. The number of lessons was decided individually by the teachers and the teachers were allowed to use any kind of sources without any limitation. The individual interviews were conducted at the interviewees' schools and were semi-structured interviews (Kvale, 1996). Semi-structured means that, on the one hand, the questions used in the interview were predetermined. On the other hand, the interviews were open for the teachers' unexpected ideas. In the semi-structured interviews, each interview consisted of three phases: the briefing and warm-up phase at the beginning, the main phase, and the debriefing phase at the end (Kvale, 1996). The briefing and debriefing phases were not audio-taped. The interview-guide is described in the appendix of Paper 2. In the *briefing phase*, the interviewer explained the procedure and purpose of the interview. The teachers were asked to give permission for tape-recording and were assured about their rights to withdraw from the interview at any time. In this warming-up, the questions concerned details of teaching experience, and what they thought about teaching chemistry and chemical bonding. In the *main phase*, the research questions were addressed. In the *debriefing phase*, the teachers were asked if they wanted to comment on the content of the interview and how they perceived the interview. The teachers again gave permission for tape-recording for research purpose, and were reminded of their rights to withdraw the tape-recording from the study at any time. The audio-taped interviews were transcribed in full.

To analyze the *representations of models* used in textbooks and by teachers, the analytical framework described in the background was used (Table 1). The *teachers' knowledge of students' difficulties in understanding* reported by the teachers in the interviews, were divided in each bonding type, and compared to those reported in research literature. The *teaching activities* were divided in categories emerged from the trends in the observed data and classified as teachers-centred or student-centred. The *influence of the textbooks* on the teachers' selection of how to represent the models of chemical bonding was indicated by the teachers' statement and by investigating the correspondence of the representations, typical examples, and order of introducing the type of bonding used by textbooks and teachers. The analysis of the textbooks as well as the lesson plans and interviews were done in an iterative process. For more details of the methods and analytical processes, see each paper respectively.

Methodological concerns, validity and reliability of the results

In the interview situation, it was considered important that the interviewee was feeling relaxed and safe in the relation to me as a researcher and to be prepared to share his or her experiences of teaching chemical bonding. Therefore, they were informed of my background as a teacher and the procedure and purpose of the research study and that I do not aim to assess their teaching or that I possess some kind of answer of the 'right and only way' to teach chemical bonding. That is, my interest was to take part of their experience and ways of teaching chemical bonding. All the participating teachers were informed that participation was voluntary, and they were assured about their rights to withdraw from the interview at any time. Further, they were guaranteed that the audio-recording should be used only for my own research purpose and not shared with anyone else, except for possible excerpts from the transcript in discussions with research colleagues. I also asked for their permission to quote them or using their representations of models from the lesson plans in a research context, for instance seminars, conferences and papers, but in that case, they were guaranteed individual confidentiality and anonymity.

With respect to the validity, the analytical framework developed to analyze the representations of models of chemical bonding is important. This framework was based on accordantly research findings from several studies regarding students' difficulties in understanding of models in general and models of chemical bonding, known for several years. Moreover, the development of the categories in this framework was discussed by colleagues that are experienced researchers, that is, the authors of the papers included in this thesis. The backgrounds of these authors are here described, since the backgrounds relate to the intersubjective validity and also the reliability in this study. Three out of the four authors are experts in the field of science education research (with two professors and one senior lecturer), and the first author is a PhD student in chemistry education as well as the main researcher in this study. The first, second and third authors are also qualified school chemistry teachers.

According to Kvale (1997), communicative validity concerns the way the researcher argues for the relevance of interpretations, and are related to intersubjective validity, that concerns the ways of review, criticizing and academic status of the persons involved in discussing the research. With respect to communicative validity and intersubjective validity, during the research process, the methods and results has been discussed and presented at research seminars and conferences. The research work such as analytical process and interpretation of results has been discussed with research colleagues. Regarding the analytical process, the whole process of data analysis was iterative and the development of the categories as well as the analysis of the textbooks, lesson plans and interviews was discussed by the authors of the papers included in this thesis.

Summary of the papers

Paper I

In this paper, chapters concerning chemical bonding in five chemistry textbooks published by different publishers for teaching at upper secondary level in Sweden. The aim was to investigate how chemical bonding models were presented in school chemistry textbooks related to the students' difficulties in understanding (concerns alternative conceptions and difficulties in understanding). An analytical framework was developed from the data together with the research literature about students' difficulties in understanding regarding models of chemical bonding as well as models in general and sources of these difficulties. The results showed that the models of chemical bonding represented in the school textbooks might cause students' alternative conceptions and difficulties in understanding chemical bonding, according to research known for several years. These results matched the findings found by other recent studies.

I identified representations that might cause students' difficulties in understanding in all school textbooks, and to a vast extent. For instance, all textbooks primary used the octet rule and focused on electronic configurations when chemical bonding were explained, octet rule was used as a primary reason for bonding, anthropomorphism were used to a vast extent in the context of chemical processes, but chemical bonds were not primary presented as due to electrostatic forces in any of the textbooks. This altogether might lead to that the students think that atoms want to have 'octets' or 'full outer shell,' and this is the reason for chemical processes to occur. Only three of the textbooks were explaining the models nature and purpose, but only to limited extent, which might be a source for students to regard models as an exact replica of the real thing and transfer macroscopic properties to particles. Further, all textbooks presented ionic bonding in terms of electron transfer and covalent bonding in terms of electron sharing. The first might be a source for the alternative conception that ionic bonds only exist between ions that had transferred electrons and identifying ionic bonding with electron transfer instead of electrostatic forces. The latter might be a source for 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. Moreover, I found hybrid models in all but one textbook and to vast extent in three of the textbooks. Hybrid models can cause difficulties in teaching and learning, and may be a form of confusion for students.

My results show that representations that might cause students' difficulties in understanding obviously exist in the textbooks, and to a primary extent. Therefore, I consider it important for teachers to critical review the textbooks, and to became aware of the importance of how the models are presented, and get knowledge of which representations might influence students' understanding negatively. This should be of importance not only for the topic of chemical bonding, but for all science education. Further, my results indicate that it seems to be a gap between research and textbook authors, and I argue that there is a need for filling in this gap between research and textbooks authors, so that scientific research can improve the development of new and better textbooks.

Paper II

In this paper, ten chemistry teachers' lesson plans about chemical bonding and semi-structured interviews with the teachers concerning their teaching were analyzed. The aim was to investigate the teachers' pedagogical content knowledge (PCK) of teaching chemical bonding in order to promote students' understanding with a focus on teachers' knowledge of students' difficulties in understanding and teaching strategies to meet these difficulties. My results showed that the teachers could specify examples of students' difficulties in understanding, and a majority of these difficulties have been discussed in research literature. Nevertheless, I found several examples in this study when the teachers were not able to specifying students' difficulties in understanding or expressed hesitance in specifying, although they are presenting chemical bonding models in a way that might cause students' difficulties in understanding, and these have been known for several years. I argue that these results indicated some lack in the teachers' knowledge of students' difficulties in understanding, a component of the teachers' PCK important for making teaching effective and able to meet students' learning difficulties. I also found that the teachers use of specific representations of models were seldom to meet the students' difficulties in understanding, and the teachers were, with few exceptions, not aware of that the representation in itself could be a source for difficulties in understanding. Therefore, I argue that there seems to be a gap between research about students' difficulties in understanding regarding models and chemical bonding and teaching practices. Regarding the teaching activities, I found that they are mostly general and especially the activities to ascertaining the students' understanding can be improved in order to promote the students' understanding. These results indicated some lack in knowledge of teaching activities as well as a deficient interaction between the components of PCK.

I identified several ways of influence of textbooks on the teachers' selection of how models of chemical bonding are represented. For instance, all but two of the teachers explicit mentioned the textbooks as a source for the lesson plans, and the order of introducing the different types of bonding were the same for the teacher as in the textbook they use, with one exception. Further, I identified several examples of symbolic and visual representations used by the teachers which were similar or even identical with the ones used by the textbooks. Moreover, the teachers mainly used the same typical examples as the textbooks. This influence might then cause problems, because, as shown in my results from Paper 1, there is a correlation between the representations of models presented in the textbooks and students' difficulties in understanding reported in research. This is in line with result reported in other recent research literature, whose authors argue that this correlation may persist if the textbooks, as my results in paper 2 showed, are used as a foundation for teaching.

Discussion

The role of textbooks and how they represent chemical bonding

In the background section, I discussed the importance of the role of the textbooks in science education, in the perspective of students as well as teachers. For instance, in the students' perspective, textbooks have a unique role as obligatory reading material (Ekvall, 2001), and to represent information (Mikk, 2000). In line with this, all teachers involved in my study said that they believe the textbooks are important for the students. In the teachers' perspective, textbooks are used as a source of the content and as a program for teaching (Nicol & Crespo, 2006; Peacock & Gates, 2000; Sikorova, 2011). This is also in line with my results, which showed that the teachers were influenced by the textbooks regarding how models of chemical bonding were represented. For instance, all but two of the teachers explicitly mentioned the textbooks as a source for the lesson plans regarding the selection of representations, typical examples and order of introducing the different types of bonding. Furthermore, I identified several examples of similar representations of models in the textbooks in use, and the teachers mainly used the same typical examples as the textbooks. Moreover, I identified that the teachers used the same order of introducing the different types of bonding as the textbook they used, with one exception. This influence had not been a problem, if the textbooks presented chemical bonding in a way that improves students' understanding. According to research literature (e.g. Taber & Coll, 2002; Justi & Gilbert, 2002), however, my results delineate that the textbooks present chemical bonding in a way that can cause students' difficulties in understanding. In fact, I identified representations in all textbooks that match all the categories used in the analytical framework, and mainly to a vast extent. I will discuss some of these findings below. This correlation between the models presented in textbooks and students' difficulties in understanding has also been found in the context of genetics (Gericke & Hagberg, 2010b), and that the teaching models used in chemistry textbooks failed to support the students' understanding of a certain aspect of content is also pointed out by Justi and Gilbert (2002b). I will point out, though, that I am assure of that textbook authors simplification of models into teaching models and for instance mix of attribute from several models are done in the best of intention, that is, to improve the students' understanding.

Representations and consequences for understanding

The main core here is the factors in the way chemical bonding is taught that can be seen as sources of developing the octet frame work (Taber & Coll, 2002), as I described in previous sections. With due respect to these factors, I found that: there is a lack of discussion in the textbooks of why chemical reactions occur; there are numerous examples of the octet rule and focus on electronic configuration used to present chemical bonding; all but one textbook primarily focused on separate atoms regarding chemical reactions; anthropomorphic descriptions are frequently used, and several of them are in consistency to language used by students (Taber & Coll); chemical bonding due to electrostatic forces are presented mainly in regards to ionic bonding, and alongside or even in the context of that bonds form to achieve noble gas shell. Consequently, the students' probably will develop the octet framework, and think that atoms want to have 'octets' or 'full outer shell', and this is the reason for chemical processes to occur (Taber & Coll).

I also found that all the textbooks introduce ionic bonding in terms of electron transfer between atoms to form ions, and all typical examples used in the section concerning ionic bonding, in all textbooks, are representing ionic bonding as the result of electron transfer. Further, I found that covalent and polar covalent bonding were presented with numerous representations in terms of electron sharing, that is, as electrons shared by two atoms in a molecule. The representation of ionic bonding in terms of electron transfer has been strongly criticised because it could lead to several alternative conceptions. Moreover, presenting ionic bonding in terms of electron transfer and covalent bonding in terms of electron sharing in addition to the octet framework, can lead to that students may discount anything which does not fit the description of bonding in terms of 'electron sharing' or 'electron transfer' (Taber & Coll, 2002).

In addition, I identified hybrid models in all but one textbook and to primary extent in three of the textbooks. This is also in line with results from analysis of textbooks in the context of models of genetics where a pronounced use of hybrid models was found (Gericke & Hagberg, 2010a; Gericke et.al, 2012). Hence, these hybrid models might be confusing for the students and difficult to learn (Justi & Gilbert, 2000, Gericke & Hagberg, 2007). Further, I found that the models' nature was only rarely discussed, and the purpose was not discussed at all, in correspondence to what is found in research literature (Grosslight et. al, 1991). The models were often presented by the textbooks as if it was a proven fact rather than a theory, which also corresponds to research literature (Treagust et. al, 2002).

I also identified possible sources for students' difficulties in understanding that have not been reported in research literature. The textbooks presented examples of molecules with polar covalent bonding in the context of covalent bonding, *before* polar covalent bonding is defined. Polar covalent bonding is then defined, without explicitly saying that the molecules of chemical compounds presented in the previous section are actually examples of *polar* covalent bonding. Furthermore, the concept of polar molecules was explained in conjunction to and in the *context of* polar covalent bonding, and the textbooks were unclear in how polar covalent bonds are related to polar molecules. I suggest that these circumstances might be a source of confusion about these concepts.

Similarly to the results regarding the textbooks, I identified that examples of representations of models for a majority of the sources for difficulties in understanding were intended to be used by all teachers. Hence, I argue that my results are indicating a gap between research of students' difficulties in understanding and teaching practices as well as development of textbooks.

Suggested changes

Based on the above mentioned, there is a need for changes in the way chemical bonding is presented to improve the students' understanding. Altered frameworks designed to overcome the reported students' learning difficulties are suggested (e.g. Nahum et al, 2008). But in my opinion, several changes can be done without adopting a totally new framework. For instance, I suggest that the textbooks, in line with the teaching model proposed by Taber and Coll (2002), should explain chemical bonding in terms of electrical forces to facilitate the students' understanding of bond polarity, electronegativity and intermolecular bonding, and to prepare for more sophisticated chemical bonding models based on quantum mechanics at university chemistry level (Taber & Coll). Further, to explicitly discuss reason for bonding, and if several models and/or attributes from several models are used, be clear about that several models are used and/or the origin of the used attributes, and how these models differ from each other and the limitations of the models. Regarding the order of introducing the types of chemical bonding, teaching covalent bonding before ionic bonding is a common practice which can lead to that student apply the 'molecule presence' to all structure (Taber & Coll). To avoid the students to do so, I suggest as proposed by Taber and Coll to teach metallic bonding first, followed by ionic bonding, and covalent bonding last, and in the context of covalent bonding to start with giant covalent lattice before discrete covalent molecules. In my study, I found that none of the school textbooks presented giant covalent lattice before discrete covalent molecule, and only one textbook presented metallic bonding first. But in contrast to what is found by Taber and Coll, none of the school textbooks introduced covalent and polar covalent bonding before ionic bonding.

Teachers' PCK of teaching chemical bonding

It is important to address that the results of the study regarding teachers' PCK were revealed based on what the teachers intended to do in their teaching situations, and I did not observe how they actually taught in the classroom. Nevertheless, this study has an important contribution to make to teaching and learning concerning chemical bonding, especially the use of representations of models to teach chemical bonding with respect to students' learning difficulties. Some of the findings could also be relevant for the teaching of models in general, in other chemistry topics as well as in other subjects, and for teachers' PCK of teaching science in general.

Regardless if PCK is seen as a transformative or integrated model, where the most common position is between these two extremes (Gess-Newsome, 1999), there are different aspects of investigating PCK: investigating the components of PCK, the interaction between these components, or the interplay between PCK and the knowledge bases PK, SMK and CK (Abell, 2008). In this thesis, the teachers' PCK were investigated with focus on the components knowledge of students' learning difficulties (concerned students' alternative conceptions and difficulties in understanding) and teaching strategies in order to promote students' understanding. Even if I did not investigate *how* the components of PCK interacted or the interplay between PCK and the knowledge bases, I did recognise lack in the knowledge of the two components as well as indicated deficient interaction between them, which should be of great importance in order to promote students' understanding because these components are essential and crucial for making teaching effective and able to meet students' learning difficulties (e.g. De Jong et al, 2005; Kind, 2009, Taber, 1995).

Knowledge of students' learning difficulties and representations

Regarding knowledge of students' difficulties in understanding, I found that the teachers specified examples of students' alternative conceptions and difficulties in understanding, and all but one said that chemical bonding is one of the topics that are difficult to understand for the students. Nevertheless, I identified several occasions in the interviews where the teachers were not able to give examples or expressed hesitance about what the students' conceptions were. Most of these specified examples have been discussed in research literature. However, there are several of the alternative conceptions and difficulties reported in research literature that were *not* mentioned by the teachers, although they are presenting chemical bonding models in a way that might cause students' difficulties in understanding, as described in the previous section (Taber & Coll, 2002). This lack might be connected to the activities used to ascertaining the understanding, as well as lacking knowledge of research results. The selection of the representations intended for use in teaching indicates that the teachers were not aware of the fact that the representation in itself could be a source for difficulties in understanding. At least, it was not revealed in this study. Hence, the knowledge of how the representations might affect the students' understanding seems to be limited. Further, I found that the teachers reason to use a specific representation of models were seldom to meet the students' learning difficulties, which indicates a deficient interaction between the components knowledge of students' learning difficulties and teaching strategies.

Knowledge of teaching activities

The teaching activities mentioned by the teachers were mostly general and not specific for the teaching of chemical bonding, for instance, teacher demonstration, lecture and solving textbook tasks. The teacher-centred activity 'showing three dimensional models of molecules or ionic lattice', and the student-centred activity 'building models of molecules' were the only activities reported that are specific for chemical bonding. These activities were also examples of teaching activities explicitly mentioned as used in order to promote students' understanding. The other mentioned examples of that were: to start a lesson with some major questions; using several typical examples; and pointing out the circumstance or concept several times. Regarding activities used in order to ascertaining the students' understanding, the most common were oral questions during lecture by teachers and students ask questions when working with textbook task. These activities might imply problems to ascertaining *all* the students, which was also mentioned by the teachers. This indicated that strategies to ascertaining students' understanding, which are considered important to be able to meet the students' learning difficulties, can be improved. These results indicate some lack in knowledge of teaching activities as well as a deficient interaction between the components knowledge of students' learning difficulties and teaching strategies.

Experience and reflection

Abell (2008) raised the question, what is the role of experience in developing PCK? That PCK develops by experience is pointed out in several of the models of PCK (Gess-Newsome, 1999; Kind, 2009). As addressed by several researchers, reflection is also an important component in developing PCK (Drechsler & Van Driel, 2008; Magnusson et al, 1999; Nilsson, 2008a, 2008b, 2009; Tuan et.al, 1995). This is in line with what my results indicate, that is, experience is not enough, because I indicated lack of knowledge regarding components of PCK and deficient interaction between them, despite the fact that the teachers involved in my study are experienced teachers. The reason for this might be lack in reflection, because four of the teachers mentioned that this interview was one out of few opportunities in several years when their teaching was discussed and reflected upon. As reported by Nilsson (2009), in the context of pre-service teachers, if teachers are encouraged to share their experience, interpret, value and learn through reflection, these experiences can contribute to development of PCK.

Regarding the role of the knowledge base SMK, this aspect is not reported in my study. It was the intention in the beginning, but I found it too difficult to distinguish between SMK and the teachers explanation intended to use for teaching. (Probably, another method might have been better for this purpose). This is in line with what is reported by Kind (2009), that SMK might be more difficult to distinguish as a separated component in an experienced teachers' PCK. It can also be sensitive to ask an experienced teacher about their SMK. In the interviews, I sometimes tried to ask these kinds of questions as a follow up to questions concerning the students' conceptions and understanding of chemical bonding. But it was difficult to distinguish SMK from explanations used to teach, because they often shifted to talk about how they usually taught. As reported by Abell (2008) investigations of PCK in science is dominated by studies of pre-service teachers, and maybe it is less sensitive to investigate pre-service teachers' SMK than in-service teachers' SMK.

Finally, I want to point out that from my own experience as a chemistry teacher, I am fully aware of teachers' pressed work situation, which is also indicted by some of the teachers involved in my study, and that I am not judging or blaming the teachers. The question of teachers' working hours is also an up-to-date issue in the debate in Sweden regarding teachers work situation. It might be difficult to find time and opportunities to read research findings, critically review textbooks and share experience and reflect upon teaching. Moreover, there is seldom a tradition in schools to do so, at least in Sweden. I think it is important to raise these issues, and to ask the question: Who is responsible for these issues? Is it the teachers, researchers, school leaders or the politicians in the commune, which is the responsible authority of the schools in Sweden? There is no simple answer to these questions, but this is of great importance, because the teachers are an important and crucial factor to realize changes in teaching practice to improve the students' learning suggested by research (Justi & Gilbert, 2002b).

Implications for teaching and development of textbooks

My results could benefit textbook authors as well as teachers, both in-service and pre-service teachers, and teacher education. According to research literature (e.g. Taber & Coll, 2002; Justi & Gilbert, 2002a), however, as mentioned, my results show that both school textbooks and teachers use representations of chemical bonding that can cause students' difficulties in understanding. Therefore, it would be of importance that textbook authors as well as teachers get knowledge of research findings. In the context of models, that is, become aware of the importance of how the models are presented, and which representations that might be a source of students' difficulties in understanding, and the importance of teaching the nature of models and their related purposes. In my opinion, there is a need for bridging the gap between research results and textbook authors as well as teaching practice. If this gap will be filled in, scientific research can improve the development of new and better textbooks as well as improving the teaching in order to promote students' understanding. The issue of bridging the gap between research and teaching practices, and the question of whose responsibility this is and how to get it done, should be of interest not only for chemistry education, but for science education in general as well.

My results also showed that teachers were influenced by the textbooks when selecting the representations to teach chemical bonding. Therefore, I consider it important in developing teachers' abilities in critically reviewing the textbooks in use. This should be of importance not only for the topic of chemical bonding, but for all science education.

Regarding the development of teachers' PCK, the importance of reflection for developing PCK is addressed by several researchers (Drechsler & Van

Driel, 2008; Magnusson et al, 1999; Nilsson, 2008, 2009; Tuan et.al, 1995). In the study reported in Paper 2, a deficient interaction between components of PCK (knowledge of teaching strategies and students' learning difficulties) are indicated. The lack of reflection, mentioned by several teachers involved in the study, might be a reason for this deficient interaction. All but one of the teachers in this study have five years or more of teaching experiences. Hence, I suggest that it would be created opportunities for in-service as well as pre-service teachers to reflect on their teaching in order to developing their PCK.

Further research

This thesis focuses on chemistry education at upper secondary level. There are also several research results of students' learning difficulties at higher levels. For instance, Coll and Treagust (2002) reported that learners at all levels, despite instruction in complex, abstract models, preferred simple realistic models to explain chemical bonding. Further, common alternative conceptions may remain despite educational higher level, even university teaching (Coll & Treagust, 2002; Nicoll, 2001; Oversby, 1996). In this thesis, an analytical framework was developed to analyze the representations for models of chemical bonding used by teachers and in school textbooks at upper secondary level. It would be interesting to use this framework to also analyze chemical literature at university level, to investigate if representations that might cause students' learning difficulties also exist at this level, and to compare the school textbooks with university literature.

Changes in the way models of chemical bonding are presented and altered frameworks designed to overcome the reported students' alternative conceptions and difficulties in understanding has been suggested (e.g. Taber, 2001; 2002; Nahum et al, 2008), as discussed in the previous section. It would be of great interest to evaluate if these altered frameworks as well as the suggested changes in representation of chemical bonding will improve students' understanding.

The role of experience for developing PCK has been emphasized (e.g. Loughran et al, 2006). As mentioned in the previous section, all but one of the teachers in this study have five years or more of teaching experience, yet the results of my study indicate deficient interaction between components of PCK and lack of knowledge regarding the components in concern. Hence, it would be of interest to investigate *what* experience and *how* experiences influence the development of PCK, a question that is pointed out by Abel (2008) as one of the future challenges for PCK research. I suggested above that this deficient interaction between components of PCK depend on the lack of reflection on the teachers' teaching, which is, as mentioned, a factor addressed by several researchers as important for developing PCK. Hence, investigations of how to best create reflecting opportunities for in-service as well as pre-service teachers would be continued.

The results of my study reported in Paper 2 were revealed based on what the teachers intended to do in their teaching situations and I did not observe how they actually taught in the classroom. In future research, it would be of interest to conduct a classroom observation to investigate how teachers teach and use models of chemical bonding and how teachers communicate with students through the use of models, and also to compare with the intended teaching.

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