Teaching and learning of chemical bonding models

Aspects of textbooks, students’ understanding and teachers’ professional knowledge

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Abstract

Despite the growing importance of science and technology in society, school students consider these subjects irrelevant and hard to learn. Teachers must therefore know how to teach science in ways that enhance students’ understanding and interest. This thesis explores various aspects of the teaching and learning of chemical bonding, an important topic in school chemistry that is primarily taught using models. Research has shown that students find chemical bonding difficult to understand, and that the use of models in science education contributes to this difficulty. I therefore investigated teachers’ knowledge of how to teach chemical bonding and ways of developing it to improve students’ understanding. To this end, I analysed chemistry textbooks and teachers’ lesson plans, and conducted semi-structured interviews with teachers about their teaching of chemical bonding. This revealed that the representations of chemical bonding used in textbooks and by teachers can cause students difficulties. The teachers were generally unaware of how these representations might affect students’ understanding, implying that their pedagogical content knowledge (PCK) could be improved. To explore ways of incorporating research findings into teaching practice and developing teachers’ PCK, I conducted a learning study in which three secondary science teachers together explored and reflected on their own teaching practice. CoRe, a method for creating detailed descriptions of what, how, and why specific content is taught, was used to enhance the reflections and make the teachers’ PCK explicit. As a result, the teachers developed their representations of chemical bonding, became more aware of students’ understanding, and were better able to motivate their actions and choices of content and strategies.

This thesis shows how professional development can bridge the gap between research and teaching practice, and how teachers’ PCK can be developed to improve students’ understanding.
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List of papers

Paper I

Representations of chemical bonding models in school textbooks – help or hindrance for understanding?
Published in Chemistry Education Research and Practice, Vol. 14, No 4, pp.589–606.
http://pubs.rsc.org/-/content/articlehtml/2013/rp/c3rp20159g

Paper II

Upper secondary teachers' knowledge for teaching chemical bonding models.

Paper III

The influence of textbooks on teachers’ knowledge of chemical bonding representations relative to students’ difficulties understanding

Paper IV

Developing science teachers’ pedagogical content knowledge - systematically reflections of teaching practice during a learning study combined with Content Representations
Bergqvist, A., Nilsson, P., & Chang Rundgren, S. N.
Submitted to International Journal of Science Education.
Authors’ contributions

Authors’ contributions to paper I

The initial research design work, data collection, and analyses were done collaboratively by the first author (Bergqvist), second author (Drechsler), and third author (De Jong) as part of a PhD project involving multiple data sets. After the data had been collected, the fourth author (Chang Rundgren) helped to develop the paper’s structure and further interpret the data, and co-wrote the paper with the first author. All four authors read and approved the paper’s content before submission.

The first author’s contributions were:
- Developing the initial overall plan and the idea for the project
- Designing the project
- Collecting data
- Constructing the analytical framework
- Analysing the data and evaluating its validity and trustworthiness
- Writing text for all parts of the manuscript
- Executing the submission process and corresponding with the editor

The second author’s contributions were:
- Mentoring during the conception of the idea, the research design, and the writing process
- Validating the data analyses

The third author’s contributions were:
- Mentoring during the conception of the idea, the design, and the writing of the first draft

The fourth author’s contributions were:
- Mentoring during the data analysis process
- Co-writing the final manuscript
- Participating in the validation process

Authors’ contributions to paper II

Based on the above-mentioned data sets in the PhD project, part of the data sets was further analysed and presented in article 2. All three authors have read and approved the paper before submission.
The first author’s contributions:
- The introductory of the overall plan and idea of the project
- Constructing the design of the project
- Collecting data
- Constructing the analytical framework
- Analysing the data by taking validity and trustworthiness into account
- Writing text for all parts of the manuscript
- Executing the submission process and the correspondence with the editor

The second author’s contributions:
- Mentoring the idea, the research design and the writing process
- Validating the data analyses

The third author’s contributions:
- Mentoring the data analysis process
- Taking part in the validation process
- Co-writing the final manuscript

Authors’ contributions to paper III

Using the data sets presented in papers I and II, a further comparison of article I and II results are presented in article III by the two authors. Both authors read and approved the paper before submission.

The first author’s contributions:
- The introductory overall plan and idea of the project
- Constructing the design of the project
- Collecting data
- Constructing the analytical framework
- Analysing the data by taking validity and trustworthiness into account.
- Writing text for all parts of the manuscript

The second author’s contributions:
- Mentoring the data analyses process
- Taking part in the validation process
- Co-writing the final manuscript
- Executing the submission process and the correspondence with the editor

Authors’ contributions to paper IV

The overall research design and learning study project presented in this paper was done in collaboration by the first author (Bergqvist) and
second author (Nilsson) first and the third author (Chang Rundgren) gave further comments on the design and over-all structure of the manuscript. All the three authors were involved in co-writing process of the manuscript. All the three authors have read and approved the paper before submission.

The first author’s contributions:
- The introductory of overall plan and idea of the project
- Constructing the design of the project
- Collecting data and transcribing data
- Constructing the analytical framework
- Analysing the data by taking into account the validity and trustworthiness issues
- Writing text for all parts of the manuscript
- Executing the submission process and the correspondence with the editor

The second author’s contributions:
- Mentoring the research design
- Involving in the writing process
- Validating the data

The third author’s contributions were:
- Commenting on the research design
- Validating the data
- Involvement in the co-writing process
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Introduction

The importance of science and technology in modern societies is increasing. However, many industrialized countries are seeing declining recruitment into scientific courses of study and careers. Science education research and international surveys such as ROSE have shown that students exhibit limited interest in studying science and technology at school because these subjects are seen as being abstract and irrelevant, at least in the school context, and difficult to learn (Sjöberg, 2000). These concerns were highlighted by the ROSE (Relevance of Science Education) project, an international comparative study designed to identify factors that learners consider important in learning science (Jidesjö, 2012). Given the importance of science education for modern citizenship and the difficulty of engaging students with scientific and technological subjects, there is a clear need to identify knowledge of effectively teaching science and promoting students’ understanding of and interest in these areas. Moreover, it is vital for teachers to be made aware of this knowledge so they can use it to enhance students’ understanding.

My academic interest in the subject matter of this thesis is grounded in my background as a chemistry teacher. When teaching, I have always considered developing my students’ understanding of the subject at hand to be central to my role. However, I found that some topics were particularly difficult for my students to understand. I tried teaching these topics in several ways without seeing any noticeable improvement, suggesting that I had not discerned the critical features of the object of learning, or identified the factors that facilitate or hinder understanding those topics. During this process, I struggled with questions such as “why is this topic so hard to understand, what am I really doing when I teach this topic, and why am I doing it?” Therefore, when I had the opportunity to join the National Graduate School in Science and Technology Education (FontD) at Linköping University in 2008, I chose to focus my research on the teaching of chemical bonding. As I became familiar with research in science education, I discovered that there was a wide range of research on students’ understanding of chemical bonding. I also found large gaps between the results of this research and teaching practices, which was
upsetting to me because so much had been learned about these issues, but I as a teacher had never heard anything about it. Because I believed that many other teachers were likely to be in similar situations, and with respect to a wider range of topics than just chemical bonding, I became interested in investigating how teachers teach chemical bonding, how the topic is presented in textbooks, and what factors influence teachers when they decide how to teach. I also wished to find ways of bridging the gap between research and teaching practice.

Models play an important role in the development and communication of scientific knowledge. However, I quickly found that there is considerable evidence indicating that the use of models in science education can cause students to have difficulties understanding the topic at hand (Grosslight, Unger, Jay, & Smith, 1991; Ingham & Gilbert, 1991; Justi & Gilbert, 2002a). As such, the use of models in science may partly explain why students consider science to be a demanding topic, and to lose their interest in its study. The didactic transposition theory (Chevallard, 1989) states that textbooks and actors such as teachers play important roles in the transformation of scientific knowledge into teachable school knowledge because models are primarily presented to students via textbooks and the actions of teachers.

Moreover, it has been reported that the presentation in textbooks influences students’ knowledge and understanding, as well as teachers’ teaching (Sikorova, 2012; Tulip & Cook, 1993; Yager, 1983). Consequently, it is important for textbook writers and teachers to recognise the importance of how the models are presented, and which representations could cause students to have difficulties understanding. Naturally, it is important for teachers to have a good knowledge of teaching science, and the more instructional strategies they possess, the more effective their teaching is likely to be (De Jong, Van Driel, & Verloop, 2005). To improve and develop teachers’ knowledge of how to teach, it is necessary to conduct science educational research, and to ensure that the resulting findings are implemented in teaching practice. That is, teachers and textbook writers must regularly learn about or be updated with recent findings from science education research (Justi & Gilbert, 2002b). Pedagogical content knowledge (PCK) is a concept and tool that is useful for
understanding, evaluating and describing teachers’ knowledge and practices (Abell, 2007; Gess-Newsome, 1999; Kind, 2009), and could thus be used to assess the extent to which teachers are aware of recent findings from science education research.

Although students’ understanding of chemical bonding models have been investigated extensively, little is known about whether teachers know how to teach these models in ways that allow students to understand their core concepts in the intended ways. During my PhD studies, my reading of previous research into students’ understanding prompted an interest in exploring how textbooks and teachers present chemical bonding models, and ways of developing teachers’ PCK of chemical bonding. Teaching is a complex process in which the components of a teacher’s knowledge are connected and integrated in an intertwined way to improve students’ learning. Learning how to teach and developing the knowledge required to become a good teacher are lifelong processes that begin during the first stages of teacher training and should continue until retirement (Luft & Hewson, 2014; Villegas-Reimers, 2003). Development of teachers’ knowledge is needed because, like all professions, teaching requires continuous growth, exploration, learning, and development (Villegas-Reimers, 2003). Several studies have emphasized the importance of reflecting on teaching experiences and students’ difficulties for developing PCK (Drechsler & Van Driel, 2008a; Nilsson, 2009; Tuan, Jemg, Whang, & Kaou, 1995). Because reflection is considered so crucial for developing teachers’ PCK, I became interested in finding effective ways of systematically organizing such reflections to improve teachers’ development.

My starting point in this research is the students’ understanding. The project began with my thoughts about my own students’ difficulties in understanding models of chemical bonding during my teaching practice, and was further developed as I became acquainted with existing research on students’ understanding of this topic. Another important factor was my growing recognition that a teacher’s knowledge of students’ understanding plays a vital role in shaping the structure of their pedagogical content knowledge. Knowledge about students’ understanding was also a key theme in the two studies
presented in this thesis, which resulted in four papers, all relating to chemical bonding models in teaching. The overall aim of this thesis is to provide various insight of the teaching and learning of chemical bonding models and ways of portraying and improving teachers’ professional knowledge to enhance students’ understanding.
Background

The background section presents the theoretical background of the work reported in the thesis and a discussion of relevant previous research. The background material addresses two main topics: (1) teaching and learning about models in general and chemical bonding models in particular, and (2) science teachers’ PCK and professional development.

Teaching and learning about models in general and chemical bonding models

There is no doubt that models play important and central roles in science and science education, including chemistry and chemistry education. However, several studies have suggested that students have difficulties understanding models in general, and chemical bonding models in particular (Gericke & Hagberg, 2007; Justi & Gilbert, 2000, 2002b; Taber & Coll, 2002). These difficulties may partly explain why students regard science as a demanding and difficult subject. The following section discusses the roles of models and related problems in science, chemistry, science education, and chemistry education.

Models in science and the related challenges in science education

The development of models is essential in the production and communication of scientific knowledge (Gilbert, 2007). When scientists try to explain an observed natural phenomenon, they develop theories, which frequently incorporate models that are linked to the observed phenomena. These models can be used to explain existing observations and predict the outcomes of new ones (Gilbert, Boulter, & Rutherford, 1998), and to make the abstract visible (Francoeur, 1997). Alternatively, a model can be regarded as a description and/or simplification of a complex phenomenon (Gilbert, 2007), or as a proposal stating how concepts, of which the world is believed to
consist, physically and temporally correlate to each other in the material world (Gilbert, Boulter, & Elmer, 2000).

A model can be defined as a representation of a phenomenon that is initially produced for a specific purpose (Gericke & Hagberg, 2007). It is important to point out that a model cannot be said to be “true”: the purpose of models is to test ideas rather than be a copy of reality, and they may be changed to accommodate new ideas (Grosslight et al., 1991). In an educational context, there is an important difference between saying that a model explains a phenomenon and saying that it describes the phenomenon. All models describe some phenomenon, but the extent to which a given model actually explains something depends on what it is supposed to explain - the value of an explanation based on a model depends on what the model is intended to help people understand and/or what we want the student to discern.

Models also play vital roles in the development of chemical knowledge (Gilbert, 2007). Chemistry deals with the properties and transformations of materials, which are essentially abstract. To understand macroscopic chemical observations, one must use models of phenomena that occur at sub-microscopic scales (Oversby, 2000). For instance, when sodium chloride is mixed with water, one can see that the salt is dissolved, and if we test the solution’s conductivity with a dipped electrode, we find that it has become a much better conductor of electricity. However, we cannot see what happened at the (sub-)microscopic level, so we need a model to make the invisible visible, i.e. to explain or describe what happened and why the conductivity changed after the salt dissolved.

Chemical ideas are presumed to have been developed and spread using visual, mathematical, or verbal models since the discipline’s earliest days (Justi & Gilbert, 2002b). The first concrete model of the atom was developed 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; as a result, modern chemists use many different models to produce and communicate knowledge about chemical phenomena (Justi & Gilbert, 2002b).
Before discussing problems relating to models in science education, it is necessary to consider the wide variety of epistemological states in which scientific models can exist (Figure 1). For example, a mental model is a private and personal representation that is created by an individual to describe e.g. some natural phenomenon (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). If scientists and researchers working in the relevant field agree that an expressed model has some predictive or explanatory value, it can be termed a scientific model, e.g., the Schrödinger model of the atom (Gilbert, 2007; Gilbert et al., 1998). Scientific models are often developed when they need to be revised, i.e. when there is no easy correspondence between the model and new observational data (Kuhn, 1996; Wimsatt, 1987). If this revised model then replaces the earlier model, the earlier model is seen as a historical model. However, historical models often remain in use because they can still serve a useful explanatory purpose in specific contexts (Gilbert, 2007). One example is that Bohr’s atomic model is often used in preference to the more recent quantum mechanical model to explain the structure of the atom at lower levels of education. When models are explained to and expressed for students, they are expressed in terms of one or more modes of representations (Gilbert, 2007). This thesis focuses on the verbal mode (spoken or written descriptions or explanations), the symbolic mode (e.g. chemical symbols, formulae, and equations), and the visual mode (e.g. graphs, diagrams, and animations) (Gilbert, 2007).

The centrality of models in science means that they play equally important roles in science education. However, the use of models in science education can cause students to perceive science as demanding and difficult to understand. This thesis pays special attention to an additional epistemological model state: the teaching model (Gilbert, 2007). These are often simplified and modified versions of scientific and historical models, developed for use in a teaching situation, and they often take the form of analogies or metaphors (Figure 1). Other teaching models are hybrids formed by combining elements of different scientific and/or historical models with different theoretical backgrounds (Gilbert, 2007) (Figure 1b). One such hybrid model is
widely used in chemistry teaching to explain covalent bonding between two atoms. According to this model, the atoms are held together by a pair of electrons that are shared between the two atoms (a concept derived from the electron-sharing teaching model), causing the atoms to be surrounded by the same electron cloud (from the quantum mechanical model of the atom) and to thereby obtain the same electron structure as a noble gas (from the octet framework), allowing one to accurately calculate how the electrons behave (from the quantum mechanical model of the atom), and then get a picture of the density of the electron cloud (from molecular orbital theory).

**Figure 1.** Description of a) the connections between the epistemological states that models attain in science and science education, showing the progression from a mental model to a teaching model, and b) the formation of hybrid models by the transference and merging of elements from different scientific/historical models.
The use of simplified scientific models can be justified, but studies have shown that many teaching models fail to support either students’ understanding of the targeted subject matter or understanding of what a model is and means (Justi & Gilbert, 2002b). The merging of elements to create a hybrid model is probably done to reduce the simplification of teaching models, but the result may be a confusing model that is difficult for students to learn. If a hybrid model is used as a teaching model, it will not provide a suitable foundation for students to develop more complex models because hybrid models consist of elements of different scientific models that students will meet in the next stage of their learning. Consequently, teaching models (both hybrid and simplified) may obstruct both teaching and learning, and can cause students to have alternative conceptions and difficulties understanding (Gericke & Hagberg, 2007, 2010; Gericke, Hagberg, Santos, Joaquim, & El-Hani, 2014; Justi & Gilbert, 2000; Thörne & Gericke, 2014). An ideal teaching model would have ‘an optimal level of simplification’ (Taber & Coll, 2002, p. 218), that is, it would be as simple as possible while still being scientifically correct, and would thus provide a foundation for students to build on later in their learning process (Taber & Coll, 2002). Important aspects of models are that they have limitations and multiple functions, and that a given concept or phenomenon can often be explained using several different models. If hybrid models are used in teaching, these aspects will be unclear to the students, which could easily create confusion. It can be argued that if students were made aware of these aspects, they would have a better understanding of scientific knowledge and the nature of science (Boulter & Gilbert, 2000; Drechsler & Van Driel, 2008b; Gericke & Hagberg, 2007).

Several studies have shown that teachers and textbooks are not always explicit when they use models in their teaching (Drechsler & Schmidt, 2005; Gericke et al., 2014). It is common for the nature and purpose of models to not be discussed at all, and for models to be described as though they themselves are the phenomena under discussion (Grosslight et al., 1991). The issue is further complicated by the fact that the teachers themselves might not be aware that they are communicating science via a model. In fact, teachers often present models as proven facts rather than theories (Treagust, Chittleborough,
& Mamiala, 2002). Therefore, students fail to clearly understand the nature and role of models (Othman, Treagust, & Chandrasegaran, 2008; Taber, 2001). This may be why students frequently consider models to be exact replicas of the real entities under consideration (Grosslight et al., 1991; Ingham & Gilbert, 1991). For instance, consider a ball-and stick model of a water molecule where the oxygen and hydrogen atoms are represented by red and white balls, respectively, and held together by sticks. Students shown this model may come to believe that oxygen atoms are red, and that the bonds between atoms consist of sticks of some kind. Such non-explicit uses of models may also explain why students tend to assume that the macroscopic properties of a substance can be transferred to (sub)-microscopic particles. For instance, they might believe that a molecule of water is liquid because water exists as a liquid (at atmospheric pressure between temperatures of 0-100 °C).

In the first study presented in this thesis, I investigated the teaching models of chemical bonding used by teachers and in textbooks and the problems arising from students’ difficulties in understanding these models, as discussed in this section and those below.

**The role of textbooks in science education**

Textbooks and teachers play central roles in the didactic transformation process whereby scientific knowledge is transformed into teachable school knowledge (Chevallard, 1989). While teachers are arguably the single most important factors affecting students’ opportunities to achieve the intended goals of learning (Hattie, 2009), several studies have shown that textbooks have tremendous influence over teachers’ teaching and students’ learning. Textbooks are used extensively to support teaching and learning in schools, and have a wide range of functions in science education (Mikk, 2000). One of my aims in the first study was to analyse how chemical bonding models are represented in textbooks and how they influence teachers’ teaching practices. This section presents previous research findings relating to the role of textbooks in teaching and learning about models.
Textbooks affect students and teachers in different ways. They are important resources for developing students’ knowledge because they contain various representations that influence students’ learning (Sikorova, 2012; Tulip & Cook, 1993). In addition, they greatly influence teachers’ decisions about what and how to teach (Nicoll, 2001; Peacock & Gates, 2000; Roth et al., 2006; Tulip & Cook, 1993) in terms of factors such as how the subject matter is structured and represented, whether specific topics are presented in detail or only briefly reviewed, and the sequence of topics (Sikorova, 2012). Studies on chemistry education have shown that textbooks are the most widely and frequently used teaching aids in this chemistry (Justi & Gilbert, 2002b). Moreover, textbooks provide the most thorough representations of curricula (Mikk, 2000), and thereby serve as curriculum guides for in-service and pre-service teachers (Mikk, 2000; Nicoll, 2001).

The influence of textbooks on teachers’ practices can create opportunities to implement new curricula and provide teachers with representations and explanations that promote students’ understanding of scientific concepts. However, several studies have highlighted problems with the role of textbooks in teaching and learning using models. As previously mentioned, teaching models and hybrid models are frequently used in textbooks and by teachers, and teachers are not always explicit about their use of models in their teaching (Drechsler & Schmidt, 2005; Gericke et al., 2014), which can be problematic. Moreover, the models presented in textbooks can fail to support both students’ understanding of the content (or some of its aspects) that the model is intended to explain and their understanding of the model’s meaning (Justi & Gilbert, 2002b), giving rise to learning difficulties (Gericke & Hagberg, 2010). In fact, it appears that the presentation of models in textbooks correlates with some alternative conceptions held by students (Gericke & Hagberg, 2010). As such, the strong influence of textbooks appears to be problematic.

Given the importance and influence of textbooks, it is important that they be systematically evaluated to identify potential shortcomings. In addition to the roles mentioned above, one of the most important functions of a textbook is to present information, which should be
scientifically correct (Mikk, 2000). Delineating the potential shortcomings of existing textbooks will create opportunities to use the results of scientific research to develop new and improved alternatives (Mikk, 2000).

Textbooks, as well as teachers, are included in the didactic transformation process where scientific knowledge is transformed into teachable school knowledge (Chevallard, 1989). Even though teachers can be seen as the individually most important factor for students to accomplish de intended goals of learning (Hattie, 2009), several research findings show that textbooks have a tremendous influence on teachers’ teaching and students’ learning. Textbooks are used extensively to support teaching and learning in schools and have a wide range of functions in science education (Mikk, 2000). On of my aims in the first study was to analyse how chemical bonding models are represented in textbooks and how they influence the teachers’ teaching practice. In this section, research illuminating the role of textbooks in teaching and learning about models will be presented.

In the perspective of students, textbooks are an important resource for developing students’ knowledge as they contain various representations that influence students’ learning (Sikorova, 2012; Tulip & Cook, 1993). In the perspective of teachers, textbooks greatly influence teachers’ decisions concerning what and how to teach (Nicoll, 2001; Peacock & Gates, 2000; Roth et al., 2006; Tulip & Cook, 1993). For instance, how the subject matter is structured and represented, if presented in detail or not, and the sequence of topics (Sikorova, 2012). Regarding chemical education, results show that the textbook has been the most widely and frequently used teaching aid (Justi & Gilbert, 2002b). Moreover, textbooks provide the most thorough representations of curricula (Mikk, 2000), and thereby serve as curriculum guides for in-service as well as pre-service teachers (Mikk, 2000; Nicoll, 2001).
Models of chemical bonding

This thesis is concerned with the teaching and learning of chemical bonding. Chemical bonding is one of the most important topics taught in chemistry at the upper secondary school level, and must be understood to study most other topics in chemistry (C. Harrison, Hofstein, Eylon, & Simon, 2008; Levy Nahum, Mamlok-Naaman, & Hofstein, 2013; Taber & Coll, 2002) because the properties of substances and their physical and chemical changes are determined by the interactions between atoms or charged particles such as ions, i.e. by chemical bonding (Coll & Treagust, 2003). Chemical bonding is primarily taught using models (Taber & Coll, 2002) because chemistry deals with the nature of substances and their transformations, which are essentially abstract concepts (Justi & Gilbert, 2002b). Because we cannot actually see how atoms or other particles are held together, students must understand models of chemical bonding to understand chemistry. Chemical bonding is an inherently complex topic, so it is not surprising that it was one of the topics that my students found most difficult to understand. and the more I get familiar with research on students’ difficulties understanding chemical bonding, the more I understand the reason for these difficulties. This section briefly reviews the most important scientific models of chemical bonding to illustrate the topic’s complexity, and to make it easier to follow the later descriptions of students’ difficulties understanding chemical bonding and the sources of these difficulties.

This thesis deals with models of ionic, covalent and metallic bonding that are not based on quantum mechanics. While quantum mechanics provides the most rigorous conceptual framework for describing and understanding chemical bonding, it is arguable that teaching chemistry from a strictly formal quantum mechanical perspective is both impractical and undesirable (Levy Nahum et al., 2013).

One traditional approach to teaching chemical bonding is to divide bonds into two main categories: intramolecular bonds, i.e. ionic, covalent, and metallic bonds; and intermolecular bonds, i.e. bonding between molecules based on dipole-dipole interactions, van der Waals forces, and hydrogen bonds (Figure 2a). A slight different traditional
approach uses a division into ionic, covalent, molecular, and metallic bonds, with molecular bonds being further subdivided into intermolecular bonds and covalent bonds (i.e. bonds between the atoms of a molecule), which are regarded as the only intramolecular bonds (Levy Nahum, Mamlok-Naaman, & Hofstein, 2008) (Figure 2b). Ionic, covalent and metallic bonds are often considered to be the most important types of chemical bond.

In the scientific literature and research in chemistry education, forces between molecules (which are sometimes discussed in terms of intermolecular bonding) are sometimes discussed in terms of intermolecular forces or non-bonding forces rather than as chemical bonds (Atkins, 1994; Hopp & Hennig, 1983; Lagowski, 1997c; Lewis & Hawley, 2007; Parker, 1997; Silberberg, 2003). In university-level chemistry, chemical bonds (i.e. ionic, covalent and metallic bonds) are described as the forces broken in chemical reactions, and are said to influence the chemical properties of matter. Intermolecular forces are described as the forces responsible for holding molecules together, and are said to affect the physical properties of matter (Silberberg, 2003) as well as the structures of solids and the properties of liquids and real gases (Atkins, 1994). The discussion below focuses on scientific models of ionic, covalent and metallic bonds as presented in the university literature. I also describe models for these bonding types based on quantum mechanics, because elements of quantum mechanical models are incorporated in some teaching models (i.e. hybrid models) that are used in textbooks and by some of the teachers examined in the first study included in this thesis. The descriptions are based on university chemistry textbooks and reference works such as chemistry handbooks, dictionaries, and encyclopaedias. Although these texts are adapted to an educational setting and therefore possibly simplified to some extent, they are likely less simplified than chemistry textbooks for upper and lower secondary schools because the university literature is intended to be closer to the scientific models. The descriptions in the following sections are partially revised versions of passages describing scientific models in university literature that were first presented in my Licentiate thesis (Bergqvist, 2012).
a) Figure 2. Traditional approaches for teaching chemical bonding based on divisions into a) intra- and intermolecular bonds, or b) ionic, covalent, molecular, and metallic bonds, with molecular bonds being subdivided into inter- and intramolecular bonds as described by Kronik et al. (2008).

**General bonding**

In university literature, chemical bonding in general is defined in terms of forces between particles, for instance as: ‘forces that hold atoms together in stable geometrical configuration’ (Lagowski, 1997b, 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 & Hawley, 2007). Silberberg (2003) explicitly notes that these forces between particles (e.g. atoms) arise from electrostatic attractions between opposite charges, and are referred to as chemical bonding.
Two reasons are commonly invoked to explain why bonding occurs in general. The first is that attractive electrostatic interactions between positive and negative particles (oppositely charged ions, or atomic nuclei and the electrons between them) lower the potential energy of the system (Silberberg, 2003); the second is that uncombined atoms are unstable and mutually attractive, which leads to chemical bond formation (Hopp & Hennig, 1983).

### Metallic bonding

Metallic bonding is explained in terms of the electron-sea model (Parker, 1997; Silberberg, 2003). In this model, the metallic lattice is described as consisting of cationic atomic cores surrounded by the metal atoms’ delocalized valence electrons, which form an ‘electron sea’ (Silberberg, 2003) of delocalized electrons (Chang, 2005). Electrostatic forces are emphasized by both Chang (2005) and Silberberg (2003), who stress the importance of the attractive interactions between these electrons and the positively charged metal cations. There are also models of metallic bonding that use the concept of the electron sea but not the term “delocalized electrons” or the emphasis on bonding as a consequence of the attraction between cores and electrons. Instead, these models describe metallic bonding as a consequence of the electrons in the sea being free to move through the metallic lattice (Parker, 1997) or between the atomic cores (Hopp & Henning, 1983). These valence electrons are also said to form a so-called electron gas that ‘glues’ the cations of the metallic lattice together (Hopp & Henning, 1983). Some literature does not use the term electron sea, but resembles the approach of Silberberg in that metallic bonds are described in terms of the attraction between the atomic nuclei and the ‘outer shell electrons,’ which are shared ‘in a delocalized manner’ (Lewis & Hawley, 2007, p.172). Other university literature (Atkins, 1994) explains metallic bonding using a quantum mechanical model based on molecular orbital theory (which is discussed below) known as band theory. Finally, Lagowski (Lagowski, 1997a) uses a model of metallic bonding in terms of ‘bands of orbitals’ that are very close in energy and are delocalized over the entire crystal, which can be seen as a concept that was heavily influenced by band theory.
Ionic bonding

The transfer of electrons from a metal to a non-metal is a central concept in the descriptions of ionic bonding presented in the university chemistry literature (Chang, 2005; Parker, 1997; Silberberg, 2003). For instance, ionic bonding is described as a type of bonding in which one or more electrons are transferred (Parker, 1997), or bonding resulting from the transfer of one or more electrons from one atom to another (Atkins, 1994). However, other texts define ionic bonding in terms of electrostatic forces rather than electron transfer. For instance, ionic bonding is defined as a consequence of the electrostatic attraction between oppositely charged atoms or groups of atoms (Lagowski, 1997) or ions (Hopp & Henning), as the electrostatic force that holds ions together in ionic compounds (Chang, 2005), or as the result of electrostatic attraction between oppositely charged ions (Lewis, 2007). However, Chang (2005) introduces ionic bonding in terms of reactions involving transfers of electrons, whereas Lewis (2007) refers to the transfer of electrons at another point in the text. An alternative description is that ionic bonds are one of the principal types of bond, alongside covalent bonds, where the particles are held together by the Coulombic attraction between ions of opposite charge, and ionic bonding can be seen as ‘a limiting case of a covalent bond between dissimilar atoms’ (Atkins, p.462). Further examples of ionic bonding as a consequence of electrostatic forces are descriptions in which oppositely charged ions are held rigidly in position in an ionic lattice by strong electrostatic attractions (Hopp & Hennig, 1983; Lagowski, 1997c; Silberberg, 2003). In some literature, the model of ionic bonding is explicitly said to explain the properties of substances; the ionic lattice is invoked to explain the fact that ionic solids are hard, rigid, and brittle, and conduct electricity when melted or dissolved in water but not in the solid state (Lagowski, 1997b; Silberberg, 2003).

The connection between energy and ionic bonding is emphasized in some literature by referring to the lattice energy. For instance, ion formation requires energy, but a large amount of energy known as the lattice energy is released when the gaseous ions form a solid. This process can also be discussed in terms of the enthalpy change when the gaseous ions form a solid (Silberberg, 2003), or the energy required to overcome the attractive forces in an ionic compound (Lagowski,
The lattice energy depends on the sizes and charges of the ions, and can be computed using a Born-Haber cycle (Chang, 2005; Lagowski, 1997b; Silberberg, 2003). The importance of the lattice energy is highlighted by Chang (2005) and Lagowski (1997b), who both state that it determines the stability of the ionic compound, and also by Silberberg (2003): ‘ionic solids exist only because the lattice energy drives the energetically unfavourable electron transfer’ (p.333). Further, Lagowski (1997b) points out that the stability of ionic compounds is not determined by the electron configuration obtained when the ions are formed.

**Covalent bonding**

Non-quantum mechanical models describe covalent bonding in terms of the sharing of electron pairs between two atoms, as proposed by the American chemist G.N. Lewis in 1916, before quantum mechanics was fully established (Atkins, 1994). This model is said to be simple but “extremely reliable” (Lagowski, 1997b, p.424), and is an example of a historical model that remains in use. Covalent bonding was explained by Lewis as the sharing of electron pairs between two atomic centres, with the electrons being placed between the nuclei and the bond resulting from the attractive electrostatic interactions between the negative shared electrons and the positive nuclei (Lagowski, 1997b). The most common approach in the university literature is to emphasize the role of electrostatic forces in covalent bonds. For instance, Chang (2005, p. 354) states that ‘each electron in a shared pair is attracted to the nuclei of both atoms’ and that this attraction is responsible for covalent bonds. Other authors describe the shared electron pair as “the glue that bonds the atoms together by electrostatic interaction” (Lagowski, 1997b, p.424), or as Silberberg (2003) puts it, 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. Here the energetic aspect is accounted for by stating that as these attractive interactions draw the two atoms closer together, there are opposing repulsive interactions between the atoms’ nuclei and electrons. The covalent bond then results from the formation of a balance between these attractions and repulsions that minimizes the
system’s energy (Silberberg, 2003). Some descriptions focus on the electronic configuration of the atoms – for instance by stating that stability is achieved if the sharing of electrons permits the molecule’s constituent atoms to obtain complete octets of electrons (Silberberg, 2003). This stands in contrast to the description of ionic bonding presented by Lagowski (1997b), which states that the stability of ionic compounds is independent of the electronic configuration resulting from the ions’ formation.

The contribution of electrostatic forces is presented in a slightly different way by Hopp and Henning (1983), who state that covalent bonds form as a result of the atoms meeting such that their electrons enter the ‘attractive region’ outside their parent atom, i.e. the electric field of the other atom’s positively charged nucleus. Bonding results from the presence of electrons between the nuclei in the region where the attractive forces generated by the two nuclei are strongest, and which the electrons preferentially occupy (Hopp & Henning, 1983). This description can be considered to have been influenced by VB theory (see below). Covalent bonding is also defined without reference to electrostatic forces, e.g. as a bond in which two electrons are shared by two atoms (Atkins, 1994; Chang, 2005), 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 electrons’ (Parker, 1997).

**Polar covalent bonding**

Polar covalent bonding is described in terms of covalent bonding with unequal sharing of electrons. This inequality is described as occurring when a bond forms between atoms with different electronegativities (Silberberg, 2003; Lagowski, 1997c), resulting in a bond with one partially negative pole and one partially positive pole (Silberberg), or a bond in which the electron density is shifted toward the more electronegative atom (Lagowski, 1997c). This unequal sharing can also be described without drawing on the concept of electronegativity, for instance by saying that the electron pair is held more closely by one of the atoms (Parker, 1997) or that the electrons lie closer to one of the two atoms in the bond because of differences in the attractive forces
acting on the bonding electron pair (Hopp & Henning, 1983). Other reasons given for the unequal sharing are that the electrons spend more time in the vicinity of one atom, which can be framed as a partial electron transfer or shift in electron density. Using this model, the electronegativity of the participating atoms can be used to distinguish between polar and non-polar covalent bonds (Chang, 2005).

Lewis (2007) does not use the term polar covalent bonds; instead, covalent bonds are said to exist on a spectrum with non-polar bonds having evenly shared electrons at one extreme and very polar bonds with extremely uneven sharing at the other. According to Atkins (1994), a covalent bond is non-polar if the electron sharing is equal and polar if it is unequal.

Models based on quantum mechanics

Two models for covalent bonding that are based on quantum mechanics are valence bond theory and molecular orbital (MO) theory. Molecular orbital theory can be used to describe ionic bonding as a special case of covalent bonding, and a model based on molecular orbital theory (band theory) describes metallic bonding.

According to the valence bond theory, ‘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 these orbitals overlap, new atomic orbitals are created that differ from those of the separated atoms. This orbital mixing is called hybridization, and the new atomic orbitals are called hybrid orbitals (Atkins, 1994; Chang, 2005; Silberberg, 2003). The valence bond 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 to the electron-group arrangement predicted by valence-shell electron-pair repulsion theory (Silberberg, 2003). The valence-
shell electron-pair repulsion theory can be used to determine the molecule’s three-dimensional molecular shape from its Lewis structure by following the principle that ‘each group of valence electrons around a central atom is located as far away as possible from the others to minimize repulsion’ (Silberberg, 2003, pp.370-371).

According to molecular orbital theory, a molecule can be described as a collection of nuclei with electron orbitals that are delocalized over the entire molecule (Silberberg, 2003), or the electrons should be regarded as being spread over the entire molecule rather than localized in a specific bond (Atkins, 1994). In the same way that an atom has atomic orbitals, a molecule has molecular orbitals with well-defined energies and shapes that result from the interactions of the atomic orbitals of its constituent atoms (Atkins; Chang, 2005; Silberberg). These molecular orbitals are said to be: occupied by the molecule’s electrons (Silberberg); spread throughout the molecule (Atkins, 1994); associated with the entire molecule (Chang, 2005); and belonging to the molecule’s whole nuclear framework (Lagowski, 1997c). According to Lagowski (1997c), covalent bonding is a quantum effect associated with an increased mobility of the electrons, which become able to move in a larger volume as a result of bond formation.

Metallic bonding can be explained according to band theory, an extension of molecular orbital theory (Silberberg, 2003). Band theory describes metallic bonding as a consequence of the formation of molecular orbitals from the overlap of the atomic orbitals of individual metal atoms when they are arranged in a three-dimensional array (Atkins, 1994), or as explained by Chang (2005), ‘delocalized electrons move freely through “bands” formed by overlapping molecular orbitals’ (p.852). The energies of these orbitals are so close together that they form a continuous band of molecular orbitals (Silberberg, 2003).

**The emphasis on models in Swedish school curricula**

The work presented in this thesis was conducted in the Swedish context. My first study revealed a gap between teaching practices in Swedish schools and research findings relating to students’ difficulties
with understanding models in general and chemical bonding models in particular. However, this outcome is contradictory with respect to the emphasis that Swedish school curricula place on the use of models in science education. Because teachers must take curricula into account when deciding how and what to teach, the following section illustrates how models are used and emphasized in Swedish school curricula.

My first study was conducted in an upper secondary school (catering to students aged 16-19) belonging to the non-compulsory school system, while my second study was conducted in a lower secondary school (catering to pupils aged 13-15) belonging to the compulsory school system (age 7-15). At both these levels, Swedish curricula specify tasks, guidelines and goals for schools. The curricula for chemistry courses and the science program in upper secondary schools, and for chemistry courses in lower secondary school, emphasize the importance of using models in teaching science.

In the curriculum for the upper secondary level, the use of models is emphasized in the program’s objectives, the subject-specific aims for chemistry, and the knowledge criteria to be used when assigning grades. The role of models in describing and explaining scientific phenomena, and the development of models, are described in the program’s objectives (Swedish National Agency for Education, 2008):

“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.”.

One objective for chemistry education specified in the aims for the subject (Swedish National Agency for Education, 2008) is to work to ensure that students “develop their ability to [...] describe, interpret,
and explain chemical processes using natural scientific models”. Another is to “develop students’ ability to reflect upon observations of their surroundings using chemical theories, models, and their own experiences”.

These examples are drawn from the curricula that were in place when the first study was conducted. The curricula were revised in the year 2011; the updated curricula placed an even stronger emphasis on the use of models. For instance, the importance of ensuring students understand the nature and limitations of models is stressed in the aims of the chemistry subject (Swedish National Agency for Education, 2011a):

"Teaching in the subject of chemistry should aim at helping students develop knowledge of the concepts, theories, models and methods of chemistry. [...] Chemistry is constantly developing in interaction between theory and experiment, where hypotheses, theories and models are tested, re-assessed and modified. Teaching should thus cover the development, limitations and areas of applicability of theories and models.”

This emphasis is reflected in the criteria for assigning grades (Swedish National Agency for Education, 2011a), which state that students should be able to "give an account in basic terms / in detail / in detail and in a balanced way of the meaning of concepts, models, theories and working methods from each of the course’s different areas”. Further, the students are required to “use these with some certainty / with some certainty / with certainty to look for answers to issues, and to describe and generalise about chemical processes and phenomena”, and to be able to, in an ascending level, “give an account in basic terms / in detail / in detail and in a balanced way of how the models and theories of chemistry are developed. Students also evaluate the validity of the models and theories and their limitations in simple / simple / balanced assessments”. Here, the bolded lists with options separated by slashes represent criteria used for grading, with criteria for higher grades appearing towards the end of the slash-delimited lists.
The lower secondary school curriculum in place when the second study of this thesis was conducted was introduced in the year 2011 (Swedish National Agency for Education, 2011b). One objective for chemistry education specified in the “Aims of the subject” section of this curriculum (Swedish National Agency for Education, 2011b) is that “teaching in chemistry should essentially give pupils the opportunities to develop their ability to [...] use concepts of chemistry, its models and theories to describe and explain chemical relationships in society, nature and in people”. The use of models is also emphasized in the specified core content of chemistry: one domain specified in the core content is that chemistry teaching for students in years 6-9 should discuss the “usefulness of the theories and models of chemistry, their limitations, validity and variability” (Swedish National Agency for Education, 2011b). The knowledge requirements for the grades state that

"Pupils can compare results with their questions and draw simple/developed/well developed conclusions with some/relatively good/good connection to the models and theories of chemistry”, and that "Pupils have basic/good/very good knowledge of the structure of materials, their indestructibility and transformation, and other chemical contexts and show this by giving examples and describing them/explaining and showing relationships between these/explaining and showing relationships between these with some/relatively good/good use of the concepts, models and theories of chemistry.”

These examples show that the use of models is considered important and emphasized in the curricula at both levels.

Chemical bonding in Swedish curricula

In the curriculum for upper secondary schools, chemical bonding was taught as part of chemistry course A (under the curriculum in place when the first study was conducted) and is currently taught in chemistry course 1 (under the new curriculum introduced in the year 2011). The syllabus of the older curriculum states that, on completion
of the course, the students should 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” (Swedish National Agency for Education, 2008). The syllabus for the new curriculum identifies materia and chemical bonding as core content: “Models and theories of the structure and classification of matter” and “chemical bonding and its impact on e.g. the occurrence, properties and application areas of organic and inorganic substances”. (Swedish National Agency for Education, 2011a).

Chemical bonding is less clearly emphasized in the curriculum for lower secondary school. However, it can be related to two core content items, which require students to know about “particle models to describe and explain the structure, recycling, and indestructibility of matter. Atoms, electrons and nuclear particles”, and “Chemical compounds and how atoms are formed into molecular and ionic compounds through chemical reactions” (Swedish National Agency for Education, 2011b). Moreover, the knowledge criteria for grade assignment require students to have

“basic/good/very good knowledge of the structure of materials, their indestructibility and transformation, and other chemical contexts and show this by giving examples and describing them/explaining and showing relationships between these/explaining and showing relationships between these with some/relatively good/good use of the concepts, models and theories of chemistry” (Swedish National Agency for Education, 2011b).

**Students’ difficulties understanding chemical bonding**

As mentioned, chemical bonding is predominantly taught using models and is a complex topic. As I quickly discovered upon becoming familiar with research on students’ difficulties understanding chemical bonding, this problem has been addressed by several different studies. These works identified chemical bonding as a topic associated with a wide range of difficulties in understanding and alternative conceptions
(also termed misconceptions in the literature), as reviewed by Özmen (2004) and Taber & Coll (2002). Various authors have concluded that these difficulties are partly due to the topic’s inherent complexity but are also partly due to the way it is taught by teachers and presented in textbooks. Alternative conceptions can be quite persistent; several of the more common alternative conceptions are retained at higher educational levels, i.e. among university students (Coll & Treagust, 2002; Nicoll, 2001).

Students’ understanding is central to my research, and previous findings concerning students’ understanding of models in general and chemical bonding models in particular constitute important background material for this thesis. These research results provided a foundation on which to develop the theoretical framework used to analyse the representations of chemical bonding models in the textbooks, transcripts of interviews with teachers, and lesson plans that were considered in the first study.

The teaching models examined in this thesis are models of the main types of chemical bonding: ionic, covalent, and metallic. In this section, I describe students’ difficulties understanding these models and possible sources of these difficulties that have been identified in the research literature. I also describe some potentially superior frameworks for presenting chemical bonding that have been suggested by research. Finally, I present the framework used to analyse the representations of models of chemical bonding in the studies included in this thesis.

Possible sources of students’ alternative conceptions and difficulties in understanding

Several aspects of the way chemical bonding is presented in textbooks and taught by teachers can be seen as sources of students’ difficulties, including the use of the octet rule and focus on electronic configurations, the focus on presenting atoms as separate entities, the lack of explanations for why bonding occurs, anthropomorphic descriptions of chemical processes, and failure to explain that chemical
bonds are due to electrostatic forces (Figure 3). If chemical bonding is taught these approaches, students may adopt a common alternative conceptual framework termed the octet framework, which then reinforces alternative conceptions and difficulties in understanding (Taber & Coll, 2002). These alternative conceptions and difficulties in understanding are summarized in Table 1.

**Figure 3.** Factors relating to the ways in which chemical bonding is presented in textbooks and taught by teachers that may contribute to the development of the octet framework, which reinforces students’ alternative conceptions and difficulties in understanding.

For example, failure to explain that electrostatic forces contribute to all chemical bonds in combination with a lack of explanations for why bonding occurs, the frequent use of the octet rule, and a focus on electronic configuration could lead to students identifying ionic bonding with electron transfer instead of electrostatic forces, a commonly reported alternative conception (Robinson, 1998; Taber, 1997; Taber & Coll, 2002). That is, the octet rule will then tend to be a feasible alternative explanation for why bonding occurs. In fact, it is common to represent ionic bonding in terms of electron transfer, for example by saying that sodium chloride is formed by the transfer of an electron from a sodium atom to a chlorine atom, yielding ions with eight electrons in their outer shells. This could also cause the alternative conception that ionic compounds contain molecules...
(Barker & Millar, 2000; Othman et al., 2008; Taber & Coll, 2002), with ion pairs being seen as molecules (Othman et al., 2008; Taber & Coll, 2002), or that atoms are present in ionic compounds and become ions when the compound melts (Othman et al., 2008). It could also lead to the alternative conception that each ion in the lattice can form only one bond (whereas, for example, each ion is ‘bonded’ to six neighbours in sodium chloride), and that ionic bonds exist only between ions that have transferred electrons (Taber, 1997, 1998; Taber & Coll, 2002), which can make it difficult to understand that ionic bonds can also form between ions that already exist.

When it comes to covalent bonding, the common failure to state that all chemical bonds have electrostatic components together with the tendency to present covalent bonding in terms of electron sharing using anthropomorphic descriptions, and to frequently resort to the octet rule may cause students to generate the common alternative conception that the shared electron pair itself is the bond, and that the electron pair holds the atoms together because it allows them to obtain a noble gas shell (Taber & Coll, 2002). The idea of the shared electron pair does not support conceptual progression, and students commonly find it difficult to build upon this idea (Taber, 2001; Taber & Watts, 2000). The common way of presenting ionic and covalent bonding in terms of electron transfer and electron sharing might lead students to not regard as a bond anything that deviates from the description of ‘electron sharing’ or ‘electron transfer’ (Taber & Coll, 2002).

The frequently used anthropomorphic descriptions of chemical processes could lead to students thinking that atoms have needs or wishes, which reinforces the development of the octet framework. If anthropomorphic explanations are used habitually, they could shift from simply standing in as an example to replacing the explanation entirely (Taber & Watts, 1996). One example of this is the “sea of electrons”, the non-quantum mechanical teaching model of metallic bonding: the students might conceptualize this sea as a vast excess of electrons, which would be charged and unstable in reality (Taber, 2001). If the anthropomorphic explanations entirely replace the intended explanations, students may not see any reason to develop the more sophisticated explanations required to understand chemical
phenomena studied at higher educational levels (Taber & Coll, 2002; Taber & Watts, 1996). This problem is exemplified by the electron sea model, which presents metallic bonding as something entirely different from covalent bonding (Levy Nahum et al., 2008). However, when metallic bonding is explained using models based on quantum mechanics, it becomes clear that the same models (based on molecular orbital theory) are also applicable to covalent bonding. Anthropomorphic explanations may also be taken literally – for instance, a student may interpret the anthropomorphic concept of ‘sharing electrons’ to mean that when a covalent bond is broken, each electron returns to its ‘own’ atom (Taber, 1998).

If the reasons why bonding occurs are not explained, students may be unable to provide correct explanations for bonding phenomena or the existence of bonds (Nicoll, 2001). Once students have developed the octet framework, they may acquire the expectation that atoms “want” to have an “octet” or a “full outer shell” and that this is why chemical processes occur (Taber & Coll, 2002). It could be argued that the students then maintain an incorrect and inappropriate reason for why bonding occurs. While the octet rule can be a useful guideline, it is not an explanation for bond formation (Levy Nahum et al., 2008).

Ionic and covalent bonds are often presented as being dichotomous, i.e. electrons are either fully transferred (ionic) or shared (covalent), and ionic bonds are due to electrostatic forces, whereas covalent bonds are due to the sharing of an electron pair. This could be why concepts such as bond polarity are unclear to students (A. G. Harrison & Treagust, 1996; Peterson, Treagust, & Garnett, 1989; Taber & Coll, 2002). For instance, students might see bond polarity as a characteristic of covalent bonds rather than representing something in between the two extremes of ionic and non-polar covalent bonds. One can look at the problem in this way: if ionic bonds are presented as being due to electrostatic forces, and covalent bonds to shared electron pairs, how could any student possibly realise that there may be intermediate types of bond? This dichotomy, where ionic and covalent bonds are presented as being fundamentally different, can also lead to difficulties understanding metallic bonding, and could explain the existence of alternative conceptions such as “no bonding exists in
metals,” “metals have some form of bonding but it is not ‘proper’ chemical bonding,” “metals exhibit covalent and/or ionic bonding” (Taber, 2001, 2003), or “metallic structures contain molecules or ions” (de Posada, 1997; Taber, 2003).

Another important factor identified by research is the sequence in which different types of bonding are introduced. Teaching covalent bonding before ionic bonding is a common practice that may cause students to try to understand all chemical structures as molecules. Thus, students might conceive of ionic lattices as containing molecules, or assume that all bonded materials consist of molecules (Taber & Coll, 2002).

According to Levy Nahum et al. (2008), the general difficulties arising from traditional approaches to presenting chemical bonding (Figure 2) are that presenting each type of bonding as being fundamentally different from the others will not foster a deeper understanding of chemical bonding, and may make it harder for students to understand that all chemical bonds are based on the same underlying principles. Moreover, if the four ideal categories of bonding (Figure 2) are over-emphasized, students may be misled and the learning process may be hindered. This is especially problematic because there are many important modern materials whose bonding does not fall neatly into any of these categories.

Table 1. Students’ alternative conceptions of and difficulties in understanding chemical bonding. Possible sources of these conceptions/difficulties are indicated when identified by research literature Students’ alternative conceptions and difficulties understanding regarding chemical bonding.

<table>
<thead>
<tr>
<th>Students’ conception (C)/ difficulty in understanding (D)</th>
<th>Research literature</th>
<th>Possible sources of students’ conceptions and difficulties understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>General bonding:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regard models as an exact replica of the real thing (C)</td>
<td>(Grosslight et al., 1991; Ingham &amp; Gilbert, 1991)</td>
<td></td>
</tr>
<tr>
<td>Bonds form so atoms can obtain complete octets (C)</td>
<td>(Taber &amp; Coll, 2002)</td>
<td>Use of octet rule and focus on electronic configurations (Taber &amp; Coll, 2002)</td>
</tr>
<tr>
<td>Bonds are sticks (C)</td>
<td>(Butts &amp; Smith, 1987)</td>
<td>Ubiquitous use of ball- and stick models (Butts &amp; Smith, 1987)</td>
</tr>
<tr>
<td>Electrons do not move within bonds (C)</td>
<td>(Nicoll, 2001)</td>
<td></td>
</tr>
</tbody>
</table>
The reactants in chemical processes are individual unbound atoms (C)  

<table>
<thead>
<tr>
<th>Intermolecular bonding is stronger than intramolecular bonding (C)</th>
<th>(Goh, Chia, &amp; Tan, 1994; Peterson et al., 1989)</th>
</tr>
</thead>
</table>

Comparing the strength between the different types of bonding (D)  

<table>
<thead>
<tr>
<th>The difference between intra- and intermolecular bonding is unclear (D)</th>
<th>(Taber &amp; Coll, 2002)</th>
</tr>
</thead>
</table>

Using the right concept but the wrong explanation (D)  

| Ionic and covalent bonding presented as a dichotomy (Taber & Coll, 2002); failure to present that chemical bonds may be due to electrostatic forces (Taber & Coll, 2002); | (Nicoll, 2001) |

Relating energy to bonding (D)  

<table>
<thead>
<tr>
<th>Conceptualizing the ionic-covalent continuum (D)</th>
<th>(Taber &amp; Coll, 2002)</th>
</tr>
</thead>
</table>

**Ionic bonding:**  

<table>
<thead>
<tr>
<th>Describing ionic bonding as the transfer of electrons (C)</th>
<th>(Robinson, 1998; Taber &amp; Coll, 2002)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Bonds are only seen to exist between ions that have transferred electrons (C)</th>
<th>(Robinson, 1998; Taber, 2003)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>The ionic lattice consists of ion pairs, which are regarded as molecules (C)</th>
<th>(Othman et al., 2008; Taber &amp; Coll, 2002)</th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>Molecules exist in ionic compounds (C)</th>
<th>(Barker &amp; Millar, 2000; Othman et al., 2008)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>The electrostatic interactions between the ions in ionic lattice are unclear (D)</th>
<th>(Robinson, 1998; Taber &amp; Coll, 2002)</th>
</tr>
</thead>
</table>

**Covalent/polar covalent bonding:**  

<table>
<thead>
<tr>
<th>Sharing electrons is covalent bonding (C)</th>
<th>(Taber &amp; Coll, 2002)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>The electron-pair in itself constitutes the covalent bond (C)</th>
<th>(Taber &amp; Coll, 2002)</th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>Covalent bonds are weak (C)</th>
<th>(Barker &amp; Millar, 2000)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Covalent bonds are between molecules (C)</th>
<th>(Taber &amp; Coll, 2002)</th>
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<table>
<thead>
<tr>
<th>Difficulty conceptualizing polar covalent bonding (D)</th>
<th>(Taber &amp; Coll, 2002)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Ionic and covalent bonding presented as a dichotomy (Taber &amp; Coll, 2002)</th>
<th>(Taber &amp; Coll, 2002)</th>
</tr>
</thead>
</table>
In contrast to the broad range of studies on students’ difficulties understanding chemical bonding, only a few studies in chemical education research have proposed new frameworks or teaching models for chemical bonding that offer new ways of presenting the topic. One such framework that has been proposed involves using a teaching model that emphasizes the importance of electrostatic forces in all types of bonding. With this approach, ionic, metallic, and molecular lattices would be used as points of origin, and the discussion of bonding would focus on physical principles. This would make it possible to avoid emphasizing atoms as separate entities and electronic configurations, with bonding being introduced as an electrostatic concept (Taber, 2001; Taber & Coll, 2002). Taber and Coll (2002) argue that such a teaching model would provide an optimal level of
simplification that provides a foundation for students to develop more sophisticated chemical bonding models based on quantum mechanics later on in their learning process, e.g. at university level. The authors also suggest teaching metallic bonding first, followed by ionic bonding, and then covalent bonding last. Moreover, when covalent bonding is introduced, they suggest starting with giant covalent lattices such as diamond before introducing discrete covalent molecules such as oxygen, hydrogen, and water. This sequence might avoid the problem of students assuming the presence of molecules in all chemical structures. A similar teaching model that stresses the involvement of electrostatic forces in all types of bonding was recently suggested by Lee and Cheng (2014).

Another altered framework is the ‘bottom-up framework’ suggested by Levy Nahum et al. (2008). These authors wanted to develop a framework that is grounded in the formal theory of quantum mechanics but still able to treat all chemical bonds on an equal footing using a small set of underlying assumptions. They argue that in the traditional approach, different types of bonding are both presented and used as different entities derived from different models. Further, they “view the traditional approach that is characterized by clear-cut definitions and rigid distinctions as an insufficient basis for rationalization of current chemical knowledge” (p.1681). In their proposed framework, chemical bonding is introduced as a continuum of related concepts instead of different types of bonding. The presentation starts with basic principles and ends with specific properties (Figure 4). The framework is based on five distinct stages. The first stage introduces salient properties of isolated atoms, with single atoms being seen as the building blocks of all chemical system. Two key concepts are introduced: Coulomb’s law and the wave nature of electrons. Electrons are presented as probability clouds of negative charge around the nucleus, i.e. orbitals. In stage two, general principles of chemical bonding between two atoms are discussed. Chemical bonding is introduced as a continuum of related concepts instead of using different types of bonding. Key concepts are energy and force, the relationship between them, and the point that stability is obtained by minimizing energy. Chemical bonding should be understood as a consequence of Coulomb’s law, but not a trivial consequence: a key
point to emphasize is the relationship between Coulomb’s law and stability in terms of the balance of attractive and repulsive Coulomb potential energies as well as the electrons’ kinetic energy. All chemical bonds regardless of type can be rationalized in terms of energy stabilisation (i.e. bond energy), and all equilibrium interatomic distances (i.e. bond lengths) as the positions where attraction is balanced by repulsion. In stage three, these principals are used to present the traditional categories of chemical bonding, but as extreme cases of various continuum scales. The continuum approach refers to the “continuum scale between extreme cases of qualitatively different bonding scenarios” (p.1683). The concept of ionic bonds should be rationalized in terms of a charge transfer that generates a positive and a negative ion, which attract each other as a consequence of Coulomb’s law, while covalent bonds are explained in terms of electron-pair bonding, charge sharing, and orbital overlap. This should be followed by stressing that the nature of bonds is that they are partly covalent and partly ionic, i.e. polar. This continuum of bonding should be related to a continuum of bond strength (Figure 5). In stage four, different levels of structure are presented, starting with molecular structure. The first structural concept to be introduced is valency; with this concept established, the atomic valence shell and periodicity are explained, Lewis dot diagrams can be rationalized, and the “octet rule” can then be presented as a guideline with respect to electron pairing rather than a reason for bonding to occur. Molecular structures are followed by structures that lack well-defined molecular sub-units such ionic giant structures. At this stage, metallic bonding is introduced as essentially covalent bonding with delocalized electrons. Another continuum scale, the electron delocalization continuum, is introduced at this point and used to emphasize the relationship between bonding type and structure. Finally, in stage five, the relationship between bonding, structure and properties is discussed, which is a key issue in chemistry. During this stage, the macroscopic and microscopic levels are linked in a logical way.

The authors claim that this framework is appropriate for students at levels ranging from high school to advanced undergraduate, depending on the degree of mathematical and physical rigour that is used.
To analyze the representations of chemical bonding used in textbooks and by the teachers involved in the first study, an analytical framework was developed based on a literature review of reports on students’ difficulties understanding models in general and chemical bonding models in particular (Drechsler & Van Driel, 2008a; Gericke & Hagberg, 2007; Gilbert, 2007; Taber & Coll, 2002) together with data from chapters on chemical bonding in the most widely used textbooks and research literature that were reviewed to identify sources of students’ difficulties in understanding. The framework consisted of 11 subcategories (Table 2). The first eight categories relate to representations used when explaining and expressing models to students, and the examples in these categories are classified as verbal, symbolic, and visual modes of representations according to Gilbert.
The categories are framed based on ways in which the corresponding representations could cause students difficulties. It should be noted that categories 3, 6, and 9 are not, by themselves, sources of difficulties. However, failure to provide any reason or an appropriate reason for why bonding occurs, not presenting chemical bonding as a consequence of electrostatic forces, and not explaining a model’s nature and purpose may count as sources. To make it easier to understand the interpretation of these categories, I have present this analytical framework shortly after discussing common difficulties.

**Table 2.** Examples of representations of chemical bonding models identified in school textbooks, teachers’ lesson plans, and interviews that could contribute to students’ difficulties in understanding according to the categories used in the analysis. The school textbooks are referred to as TB1-TB5, the teachers as T1-T10, and the quotes are translated from Swedish.

<table>
<thead>
<tr>
<th>The categories</th>
<th>Verbal mode</th>
<th>Symbolic/Visual mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Use of octet rule and focus on electronic configuration</td>
<td>“All ions formed have attained a noble gas structure, i.e. they fulfil the octet rule” (TB4, p.137)</td>
<td>Na⁺ + Cl⁻ → Na⁺⁺ + Cl⁻</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 8 1 2 8 7 2 8 0 2 8 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(TB5)</td>
</tr>
<tr>
<td>2. Focus on separate atoms when representing chemical reactions</td>
<td>“I draw the chemical equation, and show the valence electrons [...] it used to be done in terms of Lewis structures, one sodium and one chlorine [...] with an arrow that shows that this electron goes over here” (T9)</td>
<td><img src="TB1" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(TB5)</td>
</tr>
<tr>
<td>3. Reason why bonding occurs</td>
<td>“The driving force for reactions is that atoms strive to react to attain a noble gas shell configuration” (TB1, p.42)</td>
<td><img src="TB3" alt="Image" /></td>
</tr>
<tr>
<td>a. octet rule</td>
<td>“We talk about achieving a noble gas structure as some kind of driving force” (T2)</td>
<td>(TB3)</td>
</tr>
<tr>
<td>b. energy changes</td>
<td>“The atoms contribute one electron each to the communal electron pair binding the atoms together. In that way, both atoms achieve a noble gas structure and lower energy” (TB2, p.71)</td>
<td>![Image](TB1, TB2, T8 in lesson plan as a copy)</td>
</tr>
<tr>
<td></td>
<td>“I try to explain that they want to achieve a noble gas structure and when that is achieved they attain a lower energy level and become more stable.” (T8)</td>
<td>(TB1, TB2, T8 in lesson plan as a copy)</td>
</tr>
</tbody>
</table>
| 4. Anthropomorphism and chemical processes | “Both of them [ionic and covalent bonding] are a consequence of the atoms striving to achieve a noble gas shell” (TB1, p.55)  
“It’s about what hydrogen will do to become happy by attaining a noble gas structure” (T9) |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Chemical bonding presented in terms of</td>
<td></td>
</tr>
</tbody>
</table>
**a. electron transfer**  
“Electrons move from one particle to another, forming ions with noble gas structures” (TB1, p.42)  
“Ionic bonding used to be the first type of bonding discussed – one would talk about what happens to get rid of or accept this valence electron [...] I used to show how one electron jumps to the other atom” (T9)  
**b. electron sharing**  
“So if one shares [electrons] with someone else, one gets eight; that is, in a way, what covalent bonding is” (T2) |
| 6. Chemical bonding presented as a result of electrostatic forces |  
**a. ionic**  
“Ionic bonding emerges because of electrostatic attractions between positive and negative ions” (TB3, p.92)  
“Ionic crystals are held together by the attraction between positive and negative ions.” (T5)  
**b. covalent and polar covalent**  
“The negatively charged electron cloud attracts the positively charged nuclei” (TB5, p.xx)  
**c. metallic**  
“Metallic bonding: attractive forces between metallic ions and the communal electron cloud” (TB2, p.51) |
| 7. Elements of different historical models merged to form hybrid models | Two electrons form a pair that is **shared by both atoms** (electron sharing), which are then **surrounded by the same electron cloud** (quantum mechanical model of atom, QMA) and have a **noble gas configuration** (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, p.150) |
| 8. Bonded non-molecular materials presented as involving discrete molecules | “the ion pair Na⁺Cl⁻ is the crystal’s smallest ‘building element’” (TB2, p.57) |
9. Explaining the nature and purpose of models  
“We are working with models, which sort of, may not be telling the whole truth, but telling the truth in different ways. Each model has some advantages and disadvantages compared to others.” (T3)

10. Order of introducing types of bonding  
<table>
<thead>
<tr>
<th>Types of Bonding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionic, covalent, polar, metallic bonding</td>
</tr>
<tr>
<td>Metallic, ionic, covalent, polar covalent bonding</td>
</tr>
</tbody>
</table>

11. Typical examples of different bonding types  
<table>
<thead>
<tr>
<th>Bond Type</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionic bonding</td>
<td>NaCl</td>
</tr>
<tr>
<td>Covalent bonding</td>
<td>H₂</td>
</tr>
<tr>
<td>Polar covalent bonding</td>
<td>HCl</td>
</tr>
</tbody>
</table>


3 From “Gymnasieckem A”, Andersson et al. (2000, p. 41). Reprinted with permission of Per Werner Shulze, illustrator.


**Teachers’ professional knowledge**

What types of knowledge are needed to be a ‘good’ teacher? Teachers undoubtedly require a large and complex body of knowledge, and learning how to teach and develop the knowledge required to become a good teacher is a lifelong process that begins in the first days of teacher training and should continue until retirement (Villegas-Reimers, 2003). Researchers have shown a growing interest in science teachers’ professional knowledge in recent decades, and whether the teachers are professionals (as opposed to ‘workers’) has been debated for some time in many different countries (Villegas-Reimers, 2003).

Shulman (2015) claims that teachers are indeed professionals: like other professionals, teachers must develop a large and unique body of understanding, and thus deserve to be treated as professionals by the society. For teaching to be regarded as a profession, a teacher’s
knowledge base must be widely acknowledged as being both vital and acquired through specific training and education, rather than being something that could be acquired by anybody through experience alone. While practice does make a difference in the preparation of teachers, this practice has to be based on theoretical models and reflective ideas (Villegas-Reimers, 2003). In the same way, teaching cannot be reduced to theories alone; theory must be understood in relation to practice. That is to say, there is an important interaction between practice and theory (Wickman, 2014). Moreover, in addition to knowledge acquired during teacher education, teachers produce knowledge used for teaching through their own teaching experiences, and experiences of practice give rise to the largest changes (Park & Oliver, 2008). Hence, “teachers are knowledge producers not knowledge receivers. This characteristic is essential to view teachers as professionals” (Park & Oliver, 2008, p. 278).

A commonly used argument in the international debate is that the better a science teacher’s subject matter knowledge, the better their teaching (Kind, 2009). However, possession of good subject matter knowledge does not necessarily guarantee that someone will be good at teaching that specific subject. A teacher must also 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).

**PCK as an important tool in science education research**

As argued by Shulman (2015), teachers possess a unique and distinctive type of knowledge that is not found among those who are merely subject matter experts (Shulman, 2015). Clearly, multiple types of knowledge are needed, and one can talk about a practical knowledge base characteristic of science teachers. Shulman proposed the concept of *pedagogical content knowledge*, PCK, to describe this unique knowledge of teachers (Shulman, 1986, 1987). PCK can be said to represent the knowledge used by teachers in the process of teaching (Kind, 2009), and encompasses both teachers’ understanding and their
enactment (Park & Oliver, 2008). It can be described as knowledge of the teaching and learning of a particular subject, including knowledge of the subject’s essential learning demands (Bucat, 2004). PCK is more than the sum of its individual components: having knowledge of content and pedagogy is not the same as having PCK. Additionally, PCK is granular; a teacher’s level of PCK relating to one topic within a discipline (e.g. chemical bonding within chemistry) may differ substantially from their level of PCK relating to a different topic in that discipline (Smith & Banilower, 2015). Finally, PCK is a dynamic construct that describes the process teachers perform when they are confronted with “the challenge of teaching particular subjects to particular learners in specific settings” (Shulman, 2015, p. 9).

It can be challenging to get experienced teachers to express their practices or to follow the development of a pre-service teacher’s PCK (Kind, 2009). Since PCK was introduced by Shulman in 1986, it has proven to be a useful concept and tool that many researchers in science education have used to understand, describe and investigate teachers’ knowledge and practice (Abell, 2007; Gess-Newsome, 1999; Kind, 2009). The concept of PCK provides a theoretical and methodological framework for understanding and examining teachers’ skills, and structuring research on teachers’ knowledge and how it is developed (Abell, 2008; Nilsson, 2008a). Moreover, PCK has become a way of understanding the complex relationship between teaching and content through the use of specific teaching approaches (Van Driel, Verloop, & de Vos, 1998), and can offer insight into how teachers should use the content of a particular subject to promote students’ understanding. No single instrument can capture the complexity of PCK, hence, so PCK research is commonly conducted on a small scale using several different (typically qualitative) instruments (Henze & Van Driel, 2015). The research presented in this thesis was performed in this way, and was conducted within the framework of PCK.

**The origin and exploration of PCK models**

Before the mid-eighties, there had been a lot of research on the relationship between content knowledge and teaching practice, and on that between generic pedagogic skill and knowledge and teaching
practices (Shulman, 2015). However, the domain-specificity of teachers’ knowledge had not been investigated (Shulman, 2015), giving rise to what Shulman described as a “missing planet” between content and pedagogical knowledge. The concept of PCK was proposed by Shulman (1986, 1987) to bridge the gap between teachers’ content knowledge and their transformation of knowledge into instruction for students, and to assess teachers’ competence. The proposal of the concept of PCK served the purpose of introducing ‘teacher knowledge’ as a general concept and PCK as a component of this knowledge (Kind, 2009).
In 1986, Shulman 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 to then use appropriate representations or analogies to promote students’ understanding. These first three categories were later 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

As shown above, PCK was identified as one of these categories of teachers’ knowledge, 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). As previously described, Shulman argued that PCK was a distinctive and unique type of knowledge held by teachers, and he saw PCK as content knowledge transformed by the teacher into a form that makes it understandable to students. Shulman described PCK as the teachers’ knowledge of how to represent and formulate a specific subject in a way that makes it comprehensible to students. PCK thus relates to teachers’ understanding of a topic, their knowledge of instructional strategies, and other relevant knowledge. Shulman’s original key components of PCK were: (a) knowledge of students’ specific learning difficulties, and
(b) knowledge of instructional strategies and representations (Shulman, 1986, 1987). Although many models of PCK have been proposed since Shulman’s introduction (reviewed by Abell, 2007; Gess-Newsome, 1999; Kind, 2009), most retain these two original components.

The proposed models of PCK generally include knowledge about content, general pedagogy, curriculum, learners, school/context of education, assessment, and orientation (also known as teachers’ beliefs and purposes) (Kind, 2015). PCK models can be classified with respect to the way they describe the interactions between the constituent knowledge bases of the PCK construct: one group of models describes these knowledge bases as being integrated (integrative models) and the other describes them as being transformed (transformative models) (Gess-Newsome, 1999). Most transformative models treat subject matter knowledge as a separate knowledge-base, whereas most integrative models do not separate SMK from PCK. The difference between science and school science in terms of subject matter knowledge has also been highlighted (Gericke, 2008; Kind & Taber, 2005). This difference implies that as a teacher gains experience, they may start using their subject matter knowledge in new ways, and its characteristics may change. As a result, it may become increasingly difficult to distinguish subject matter knowledge from other elements of their PCK (Kind, 2009).

Despite their usefulness, neither transformative nor integrative models offer any mechanism that describes combined integration and transformation processes (Kind, 2015). Kind suggested that a transformation process is more likely for pre-service teachers, who transform their (often recently-acquired) subject matter knowledge (Kind, 2015). Experienced teachers do not seem to transform their subject matter knowledge so much when deciding how to teach; their academic subject knowledge is dominated by curriculum and assessment requirements, and over time curriculum knowledge becomes the main driver of their activities, while their up-to-date subject knowledge degenerates (Kind, 2015). Kind also found that content knowledge was embedded in pre-service teachers’ PCK statements, which reduced the need to find transformative
mechanisms; she thus argues that the distinction between transformative and integrative models is irrelevant.

PCK models can also be classified with respect to the way they combine Shulman’s seven original components of teachers’ knowledge within PCK; when doing this, it is important to note than some authors use different names for the same components (Kind, 2009).

A criticism of Shulman’s model is that it lacks a theoretical background. Kind (2015) argues that the PCK construct is implicitly underpinned by the constructivist perspective, even though Shulmans’ original proposal of PCK is not explicitly presented as being based on any particular theoretical perspective (the same is true for a number of more recent PCK models). Some PCK models are however based on explicit theoretical perspectives. For example, Rollnick and Mavhunga grounded their model on the four knowledge domains suggested by Cochran et al. (1993), which are based on constructivism. Another example is the model proposed by Schneider, who connects PCK to learning progression.

One very widely used model of PCK in science education research is that of Magnusson, Krajcik, and Borko (1999) (e.g.Berry, Loughran, & van Driel, 2008; De Jong et al., 2005; Nilsson & Van Driel, 2010). In this model, subject matter knowledge is a separate knowledge-base and the components of PCK are: a) knowledge of instructional strategies, b) knowledge of students’ understanding, c) knowledge of assessment, d) knowledge of the goals and objectives of the topic in the curriculum, e) orientations toward teaching science. The first component concerns knowledge of representations and activities, whereas the second includes requirements for learning certain concepts, areas that students find difficult, approaches to learning science, and common alternative conceptions. The instructional strategies may be specific to particular subjects or topics.

Because there are so many proposed models of PCK, there is a lack of shared definitions and conceptualization. To address these weaknesses and strengthen the concept of PCK as well as the associated research community, a PCK research summit was recently organized. This
international meeting drew several researchers with interests and experience in the field of PCK. A recently presented model, the consensus model, originated at this summit and was refined and presented by Gess-Newsome (2015). This model “identifies the overarching role of teachers’ professional knowledge and situates PCK within that model, including all of the complexity of teaching and learning” (Gess-Newsome, 2015, p. 30). This model of teachers’ professional knowledge and skill includes PCK and influences on classroom practice and students’ outcomes. It thus addresses the weaknesses in several of the proposed PCK models, notably by taking into consideration students’ outcomes, context, and the curriculum (Kind, 2015). It also addresses some weaknesses of Shulman’s original proposal such as its neglect of emotions, affect, feelings, motivations, and limited emphasis on pedagogical action and social and cultural context (Shulman, 2015). Consequently, the consensus model tries to accommodate most of the aspects that are included in the various models of PCK that had been proposed before. It also includes a new category of teacher knowledge, “topic-specific professional knowledge”, which emphasizes that content for teaching is defined at the topic level.

Although many models of PCK have been proposed since Shulman’s introduction of the concept, most retain the two original components: knowledge of students’ specific learning difficulties, and knowledge of instructional strategies and representations (Kind, 2009). In the consensus model, knowledge of students’ understanding, (content) representations, and instructional strategies fall within the category of topic-specific professional knowledge, and are seen as distinct components of the model. It can be argued that knowledge of students’ understanding, representations and instructional strategies are essential for several reasons. For example, a student’s alternative conceptions can obstruct effective learning because they can hinder comprehension of subsequent related concepts (Taber, 1995). Hence, knowledge of students’ alternative conceptions plays an important role in shaping PCK (Park & Oliver, 2008). This implies that teaching a particular topic has the possibility to became more effective for the teacher by giving them better knowledge of students’ difficulties in understanding and a well-stocked repository of representations and
activities for use (De Jong et al., 2005). Notably, the quality of an individual’s PCK depends on coherent integration and interaction of the individual PCK components as well as the strength of each individual component (Park & Chen, 2012). Two components – knowledge of students’ understanding, and knowledge of representations and instructional strategies – appear to play a central role in controlling the interactions between the PCK components and, by extension, in shaping a teacher’s PCK structure.

The research presented in this thesis was inspired by both the consensus model and the model proposed by Magnusson, and places particular emphasis on the three components highlighted in the preceding paragraph.

**Development of PCK**

Regardless of which model one uses to describe or explore PCK, it is important to focus on the processes that affect PCK development (Nilsson, 2008a). Development of teachers’ knowledge is needed because, like all professionals, teachers have a constant need for growth, exploration, learning, and development (Villegas-Reimers, 2003).

The development of PCK can be understood as a constructivist and non-linear process, where new knowledge is built on prior knowledge from different domains and on experiences of practice, including interactions with students and colleagues (Clarke & Hollingsworth, 2002). Seen from a socio-cultural and situated perspective, learning is a process that entails participation in sociocultural practices that structure and shape cognitive activity (Lave & Wenger, 1991).

Both experiences and reflections are considered key components in the process of developing PCK. 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. The importance of teaching experience has been described as follows: “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, Berry, & Mulhall, 2006, p. 9). However, teaching experience without reflection is not necessarily enough to spur the development of teachers’ PCK: recent studies have underlined the importance of reflection on teaching experiences and students’ difficulties as well (Drechsler & Van Driel, 2008a; Nilsson, 2009; Tuan et al., 1995). Reflection is particularly important; the relationship between experience and reflection can be explained by saying that experiences contribute to PCK development if teachers are encouraged to share their experience and to interpret, value and learn through reflection (Nilsson, 2008b, 2009). As argued by Wickman (2014), teachers should ask themselves why they choose specific representations or activities, and be able to justify their choices. Moreover, reflection is very important for improving the integration of PCK components (Park & Oliver, 2008), and active reflection allows the growth of one knowledge base to enhance that of another (Gess-Newsome, 2015). Since reflection is important for the development of PCK, one can conclude that it is important to identify and provide effective models for systematic reflection on teaching practices that enhance the connections between individual PCK components and the strength of each individual component.

**Teachers' professional development**

Professional development can be viewed as a teacher’s ongoing learning experience that begins during the first stages of teacher training and continues until retirement (Luft & Hewson, 2014). It is a complex process whose importance is illustrated by the following statement taken from the model of the teacher learning process in professional development programmes proposed by Luft and Hewson (2014): “[teaching is] ontologically related to learning and therefore without meaning in its absence” (p.902). It is vital for teachers to be seen as active participants in their own growth and development (Villegas-Reimers, 2003).

It is important for teachers to have access to high-quality professional development at both the pre-service and in-service levels (Gess-
Newsome, 2015), and specific interventions in professional development programmes can help to enhance teachers’ PCK. It is generally accepted that teachers must participate in professional development activities to improve their teaching practice and student learning (Luft & Hewson, 2014). Moreover, studies have shown that the quality of teachers’ practice is related to the number of hours they have spent on professional development (Luft & Hewson, 2014). As with the development of teachers’ PCK, the importance of reflection in this process has been emphasized. To develop in their professional role, teachers must reflect on their teaching systematically. As Glatthorn puts it, “Teacher development is the professional growth a teacher archives as a result of gaining increased experience and examining his or her role systematically” (1995, p.41). To design effective professional development programmes (and pre-service or in-service teacher education), it is important to understand the nature of science teachers’ PCK, how it develops over time, and how it relates to other knowledge components such as general pedagogic knowledge and content knowledge (Henze & Van Driel, 2015).

School improvement requires the development of a strong capacity for change and support for teachers’ professional development (Hargreaves & Fullan, 2012). To this end, and to ensure that teachers’ professional development influences their practice in the long term, there is a need to view professional development as something that entails work with and by teachers, instead of something that is done to teachers (Nilsson, 2014). The latter approach can be seen as a ‘top-down’ approach to professional development, in which development involves process of doing to and for teachers. Thus, the teachers are seen as being passive and resistant, and development as something they must be compelled to do; the assumption is that teachers’ lack of knowledge can be remedied through training. Although they are considered responsible for implementing the desired changes, the teachers have little influence (if any) over the structure of those changes (Nilsson & Loughran, 2012). Such approaches are expected to be less successful than ‘bottom-up’ approaches (Nilsson, 2014) in which teachers learn in response to perceived needs, issues, and concerns. To clarify the differences between these two approaches to teachers’ professional development clear, the term learning can be
used instead of development. As stated by Loughran (2006, p.136): “Professional learning is not developed through simply gaining more knowledge, rather, professional learning is enhanced by one becoming more perceptive to the complexities, possibilities and nuances of teaching contexts”.

It has been shown that desired changes in teachers’ enacted instructional practices that are integrated into a professional development programme can be successfully implemented if the teachers become active learners in the programme (Luft & Hewson, 2014). It has also been concluded that professional development (or learning) that is topic-specific and classroom-embedded is much more effective than development exercises that focus on generic teaching strategies that teachers must then transfer to some specific topic (Gess-Newsome, 2015). A separate study showed that teachers found value in focusing on instructions and the content knowledge that was meant to be conveyed in their lessons, and that this focus improved their content knowledge and PCK (Luft & Hewson, 2014).

Since a teacher’s knowledge is a complex construct consisting of several components and their interconnections, all of which will evolve over time, it is difficult to design effective professional development programmes. There are several characteristics that can be considered important for effective professional development (Villegas-Reimers, 2003): teachers should be seen as active learners who learn over time; they should be encouraged to relate prior knowledge to new experiences; development should be a process that takes place within a particular context, is related to classroom experiences, is based in schools, and is related to daily activities of teaching; and the development process should be collaborative, with the teacher being seen as a reflective practitioner. Collaboration is important for supporting teachers’ growth, and is a necessary but not sufficient feature of professional development programmes with the potential to effectively change teachers’ practices (Luft & Hewson, 2014).

Even if all these issues are taken into account, professional development programmes may not have straightforward impacts on teachers’ practice because practice is also affected by the teachers’ beliefs, orientations, prior knowledge, and context-specific factors.
(Gess-Newsome, 2015). Moreover, there is no ‘best form’ of PD; effective PD interventions for different settings can look very different (Villegas-Reimers, 2003). Teachers have individual instructional requirements and change in different ways, and therefore need different forms of support to change their practice (Luft & Hewson, 2014). It is therefore essential to consider context in any professional development programme.

A model for examining professional development programmes proposed by Luft and Hewson (2014) involves four organizing components: policy, professional development programmes, teachers, and students. Teachers are the participants, and most research in this area focuses on teachers’ learning, change, or practice (i.e. studies tend to focus on the programmes’ impact on the participating teachers). It has been concluded that professional development opportunities can improve student learning, and students’ learning outcomes are an important measure of a programme’s success, but an effective programme should benefit both teachers and students (Luft & Hewson, 2014). In this model, teachers are seen as professional and adult learners with an interest in and control over their continuing professional development. It is also assumed that such programmes intend to integrate teachers’ new learning into their teaching practice in order to improve their students’ learning (Luft & Hewson, 2014). In addition, the teachers’ classroom practice is seen as an important outcome of the professional development programme (Luft & Hewson, 2014).

Taking these requirements for effective professional development into account, the second study of this thesis explored how interventions based on the framework of a learning study using the tool Content Representations (CoRe) could enhance teachers’ professional learning. These interventions are described in following sections.

**Content representations, CoRe**

Content representations, CoRe, is both a research tool for assessing science teachers’ understanding of the content they teach and a way of
representing this knowledge (Loughran, Mulhall, & Berry, 2004). When a CoRe is constructed, a teacher’s PCK are made explicit by systematic reflection on their teaching practice. CoRe was devised by Loughran et al. (2004) and is a detailed description of what, how and why a particular content is taught. It has been used in a variety of ways in science education. For example, many science education researchers have used it as a research tool for collecting data, teachers have used it to aid curriculum planning, it has been performed as a professional development activity, and it has been used to introduce pre-service teachers to PCK and to develop their PCK (Cooper, Loughran, & Berry, 2015). A CoRe emphasizes the point that the development of PCK is about conceptual understanding of the content for teaching, not about knowledge as information for the students (Cooper et al., 2015).

CoRe is an activity that was designed to get teachers to think about, and share with others, their knowledge about how to teach specific science content (Loughran et al., 2004). When a CoRe is constructed, teachers are considering what they are doing when they teach a specific topic, as well as how and why they do it. First, teachers consider and tabulate what they perceive as the main ideas or concepts involved in teaching a particular topic, which are referred to as ‘Big Ideas’. The teachers then consider each Big Idea in terms of a number of framing questions/prompts such as: what must students learn about each big idea, why is this idea or concept important for them to know, what difficulties in understanding might they encounter, what are the difficulties or limitations associated with teaching this idea, what teaching procedures will be used to teach the idea and why, how can students’ understanding be assessed, and what knowledge do the teachers hold that connects one idea or concept in the CoRe to others (Loughran et al., 2004).

The construction of Big Ideas plays an important role in framing teachers’ thinking about a particular topic because it brings the conceptual nature of the topic to the surface in new ways (Cooper et al., 2015). Moreover, the prompts of the CoRe provoke teachers to develop a deeper understanding of the content, and require consideration of how the content might be taught as well as how it might (or might not) be learned. Many studies have shown that the task of developing a
CoRe challenges teachers’ thinking. Teachers often struggle to construct Big Ideas and address the CoRe prompts when working individually CoRe (Cooper et al., 2015). Therefore, it can be helpful to work collaboratively, and to use a facilitator to stimulate and focus the group discussion (Cooper et al., 2015).

PCK can be difficult to examine and portray; CoRe offers a way of overcoming this difficulty while addressing the various issues and problems discussed above (Loughran et al., 2004). The construction of a CoRe can thus help teachers to articulate and discuss their understanding of teaching and learning a specific topic. Moreover, constructing a CoRe can enhance teachers’ professional knowledge of teaching practice, and thereby their professional development (Cooper et al., 2015).

**Learning study and variation theory**

A learning study is a tool for improving professional learning and contributing to teachers’ professional development that have been used by many researchers in science education (e.g. Adamson & Walker, 2011; Ling & Marton, 2011; Nilsson, 2014; Pang & Ling, 2012; Vikström, 2014). In a learning study, teachers collaboratively (with or without researchers) and systematically explore and reflect on their own teaching practice in order to identify the critical aspects of students’ learning. The procedures and methods used in a learning study may vary. One method, which was used in study 2 of this thesis, involves conducting research lessons in two or more cycles (Ling & Marton, 2011; Pang & Ling, 2012) (Figure 6). In this method, the teachers (and researchers) plan a research lesson and then teach it over one or more cycles. The lessons are observed, evaluated, and revised by the teachers between each cycle. The differences in the teachers’ enacted teaching between the cycles are then carefully analysed and compared to the students’ learning outcomes. These evaluations and revisions allow the teachers to develop their teaching practices and enhance their students’ learning.
Figure 6. Steps in a learning study involving cyclical repetition and refinement of the research lesson.

Variation theory

The first learning study was carried out in Hong Kong in 1999, and the method has since been adopted and developed in other parts of the world (Ling & Marton, 2011). The process is very similar to that of a lesson study, but a learning study is guided by variation theory, which is not always the case for lesson studies (Ling & Marton, 2011). Variation theory is a learning theory that provides a theoretical framework for understanding some of the necessary conditions of learning (Ling & Marton, 2011; Marton & Booth, 1997; Runesson, 2005).

According to variation theory, learning is always directed at something, for example, a phenomenon, object, skill, or aspect of reality (Ling & Marton, 2011). Moreover, learning must result in a qualitative change in how we experience and see this ‘something’ (Ling & Marton, 2011; Pang & Ling, 2012). This ‘something’ is called the object of learning. When a learner comes to see the object of learning in a new way, he or
she will probably understand and deal with it differently, and hopefully perceive it in a more powerful way (Ling & Marton, 2011).

The process of learning is described by Ling and Marton (2011) as follows. To be able to see or experience an object in a certain way, the learner must be aware of its distinguishing aspects. Moreover, they must discern these aspects at the same time. What aspects the learner discerns simultaneously and how they are related, determines how the learner sees, experiences or understands the object. These aspects are considered critical for seeing the object in the intended way and are thus referred to as critical aspects. When learners fail to learn, that is, do not see the object as intended by the teacher, it may be because they focused on non-critical aspects (not all aspects are critical) or because they did not focus on all the critical aspects (and their interrelationships) simultaneously.

According to Pang and Ling (2012), learners will only be able to discern certain critical aspects if they have experienced variation in those aspects. The authors use the aspect ‘colour’ as an example: to discern the aspect colour, one must have experienced at least two different colours. That is, learners must experience a difference in the aspect’s value. Another example used by the authors and by Ling and Marton (2011), is gender as a critical aspect of a person. One must experience the difference between male and female to be able to discern the concepts of male and female. That is, the dimension of variation (gender) must be experienced at the same time as its value (male and female). Male and female are then values that constitute a dimension of variation (gender in this example). As claimed by Marton (2009), one cannot discern without experiencing difference, and one cannot experience difference without a simultaneous experience of at least two relevant things.

Ling and Marton (2011) argue that teachers should not only present the target of learning but also the alternatives; for example, if teaching about shapes, they should explain what a triangle is and also show some shapes that are not triangles. Moreover, they argue that one should focus on differences rather than sameness. Generalisation should be introduced after contrast because generalization cannot help
learners to discern critical aspects, only to distinguish between critical and non-critical aspects. For example, the angle sum is critical for determining whether a polygon is a triangle, but the sum of its internal angles is not.

Teachers should use variation in three ways when performing a learning study (Pang & Ling, 2012). The first is to exploit variation in students’ ways of seeing the object of learning, i.e. variation in the students’ experiences or understanding of the object of learning. The second is to consider the variation in their own ways of seeing and dealing with the object of learning, by sharing knowledge about how to handle the object of learning with the other teachers participating in the study. The third is to use variation as a guiding principle for pedagogical design, i.e. to design lessons using specific patterns of variation in which certain aspects are varied and others are held constant. For example, if a teacher presented their students with three balls of the same size, shape, and material, but each of a different colour, it is likely that the colour of the balls will be discerned (Pang & Ling, 2012). Conversely, if all the balls are the same colour but their sizes differ, size is the aspect most likely to be discerned.

To summarise, variation theory provides a set of guiding principles that teachers can use when they engage in pedagogical design, lesson analysis, and evaluations of their teaching (Pang & Ling, 2012). It can explain and predict the relationships between what occurs in the classroom and what students learn, and help identify ways to improve students’ learning by promoting teachers’ professional learning in a learning study setting (Pang & Ling, 2012). I will end this section with a quote that illustrates the thinking behind the learning study approach: “although teachers cannot make their students learn, they can help make learning possible” (Ling & Marton, p.11)

**The learning study approach**

The main research problem in a learning study should always be “how can the object of learning ‘X’ be taught so that students can see ‘X’ in the intended way?” (Pang & Ling, 2012, p. 593). During a learning
study, both the teachers and the students learn and develop a deeper understanding of ‘X’. Moreover, teachers develop PCK about how to deal with ‘X’ (Pang & Ling, 2012). Ling and Marton (2011) pointed out that teachers must be aware that the intended object of learning may not be the same as the enacted object of learning or the lived object of learning. That is, what the learners experience may not be the same as the enacted object of learning. Consequently, there are always students who learn as intended, and students who do not. This dynamic quality of the object of learning gives rise to three important questions to answer and learn from during a learning study (Pang & Ling, 2012): 1. What is the intended object of learning, i.e. what should students learn during the lesson?; 2. What is the enacted object of learning, i.e. what actually happens in the lesson?; and 3. What is the lived (experienced) object of learning, i.e. what do students actually learn by participating in the lesson? By dealing with these questions, teachers strengthen their understanding of the relationship between teaching and learning. Thus, a learning study “focuses on the relation between the content, the teaching and students’ learning” (Nilsson, 2014).
Aims and research questions

As mentioned in the introduction chapter, the overall aim of this thesis is to provide various insight of the teaching and learning of chemical bonding models and ways of portraying and improving teachers’ professional knowledge to enhance students’ understanding.

In more detail, the overall aim can be divided into four sub-goals, each of which is addressed in the four appended papers (Figure 7) and provides insight into various aspects of the research questions. The four papers are tied together by several issues. First, the context of all papers is chemical bonding. Second, all papers focus on students’ understanding. Third papers II, III and IV deal with teachers’ knowledge and the concept of PCK: The aim of paper II was to investigate upper secondary chemistry teachers’ expressed knowledge of how to teach chemical bonding models, with a focus on their knowledge of student understanding, representations, and instructional strategies. In paper III, the aim was to investigate the influence of textbooks on the teachers’ selection and use of representations when teaching chemical bonding models that could cause students’ alternative conceptions and difficulties understanding. The aim of paper IV was to investigate how interventions such as learning study and Content Representations (CoRe) might enhance teachers’ reflections and development of pedagogic content knowledge (PCK). The aim of paper I was to investigate how chemical bonding models are represented in school chemistry textbooks and to relate these representations to their effects on students’ understanding. Together, these four papers provide new insight into the teaching of chemical bonding and how it can be improved to enhance students’ understanding.

The overall question that this research aims to answer is:

How can the teaching and learning of chemical bonding be captured and understood within teachers’ intended and enacted practice, and the relationship between them?
In the four papers, several specific research questions have been posited in order to more fully outline the research in this thesis, summarized below:

Paper I:
- 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 II:
- What do teachers know about alternative conceptions and difficulties understanding for students regarding chemical bonding?
- How do their representations of chemical bonding models and instructional strategies, as described by the teachers, address students’ alternative conceptions and difficulties in understanding?

Paper III:
- How do the sequence and manner in which models are presented in textbooks correlate to the sequence and manner in which they are presented by teachers?

Paper IV:
- How are components of PCK expressed and integrated within the teachers’ reflections

![Diagram](https://example.com/diagram.png)

**Figure 7.** The relationship between the two studies and the four papers included in the thesis.
Methodology and Methods

This section describes the methodology and methods applied in the studies that this thesis builds on, which are described in the appended papers. First, I will present the research design, and reasons for the choice of methods and a discussion of methodological concerns. Second, I will describe the participants, context and instruments that are used. Finally, I describe the qualitative analysis procedures, describe and discuss the validity and trustworthiness of the applied methods, and review the ethical considerations that arose. Further details of procedures, participants, analysis and so on are presented in the methods sections of the papers.

Research design and choice of methods

The research presented in this thesis was conducted within the framework of PCK. Underpinning the chosen qualitative methods was the assumption that learning occurs on many planes simultaneously, and that understanding of an object is constructed individually but is also influenced by social interactions and context. As described by Larsson (2013, p. 27) “both cognitive and human acquisition of knowledge perspectives can be helpful for illuminating the processes involved”. Under the framework of distributed cognition, cognitive processes are held to involve internal mental processes, social interactions with artefacts or other human beings, and cultural factors (Dahlbäck, Rambusch, & Susi, 2012). Additionally, the sociocultural perspective emphasizes that teaching and learning happen in communities of practice rather than in a social or cultural vacuum. This approach is also applied in social constructivism, which focuses on the learning that occurs as a result of interactions, enabling the application of constructivists’ theory of knowledge to social settings (Hung, 2001). From this perspective, people construct knowledge in collaboration with others (Prawat & Floden, 1994). However, while knowledge is constructed socially, it is then assimilated by individuals. The origins of the social constructivist approach can be attributed to the work of Vygotsky (1934/1986), who stressed that culture and social context are important for cognitive development, and that interpersonal
connections are crucial components of the learning process. Moreover, new knowledge must relate to prior knowledge and experiences, which also influence the learning process (Larsson, 2013), and as highlighted by Dewey (1938), learning is dependent on how the person reflects on his/her experiences and the activities in which they participate.

In my view, it is reasonable to suggest that the perspectives discussed above underpin the framework of PCK to some degree. Kind also argues that the constructivist perspective can be seen as an underpinning perspective on PCK (Kind, 2015) even though Shulman’s original proposal of PCK and some other PCK models are not explicitly described as being based on any theoretical perspective. However, some models of PCK are explicitly based on theoretical perspectives such as those proposed by Rollnick and Mavhunga, and by Schneider (Kind, 2015).

Every study included in this thesis used qualitative research strategies. Qualitative researchers often use inductive approaches where the researcher is intimately involved in the data collection, and thus is an important part of the research process (Gibbs & Flick, 2007). This thesis focuses on investigating teachers’ PCK and how this knowledge can be developed, which is a complex process in which the components of PCK interact dynamically. A hallmark of case studies is that observations are significant rather than frequent, and that they offer the researcher insights into the real dynamics of situations and people relevant to the object of study (Cohen, Manion, & Morrison, 2007). Moreover, this thesis examines cases and phenomena in their real-life context, uses many types of data, and focuses on individual actors (e.g. the teachers in the first study) or groups of actors (e.g. the teachers in the second study). Therefore, a case study approach was adopted in the two included studies (Cohen et al., 2007). The in-service teachers who opted to participate in these studies are treated as cases within the context of chemical bonding teaching practices at the upper secondary (first study) and lower secondary (second study) levels.

According to Cohen et al. (2007), possible advantages of case studies are that they are “a step to action”, begin in a world of action as well as contributing to it, and provide unique examples of real people in real
situations. A strength of case studies is that they observe effects in real context, and recognize context as a powerful determinant of both causes and effects (Cohen et al., 2007). Because contexts as described by Cohen et al. are unique and dynamic, case studies investigate and report on the complex dynamics and revealing interactions of events, human relationships, and other important factors in some specific situation. Additional strengths of case studies are that they are strongly rooted in reality and provide insights into other, similar situations or cases, facilitating interpretation of such situations. Moreover, they can capture unique features that may prove vital to understanding the situation but would be lost in a data gathering exercise performed on a larger scale (Cohen et al., 2007). Case studies typically do not seek to acquire observations at a high frequency and so can replace quantity with quality and intensity. In other words, they can be seen as separating “the significant few from the insignificant many instances of behaviour” (Cohen et al., 2007, p.258).

Although the overall aim of the thesis is to provide various insight of the teaching and learning of chemical bonding models and ways of portraying and improving teachers’ professional knowledge to enhance students’ understanding, each paper included in this thesis addresses different aspects of the teaching and learning of chemical bonding models. Therefore, different methods of data collection were used in each study to collect reliable data and address the different research questions posed in each paper.

**Design of the studies**

The data on which this thesis builds comes from two studies on the teaching and learning of chemical bonding. An overview of the studies and papers is presented in Figure 8. The first study focuses on how chemical bonding models are represented in textbooks and by teachers relative to students’ difficulties in understanding, and the influence of textbooks on teachers’ knowledge of how to represent chemical bonding models. This study was inspired by the case study approach, and designed as a small-scale explorative study using the Lesson Preparation Method (Van Der Valk & Broekman, 1999). This method
has been successfully used by several researchers to explore teachers’ PCK (De Jong, 2000). It usually relies on two main sources of data: (a) teachers’ prepared lesson plans, and (b) individual semi-structured interviews with teachers. The study therefore focused on the teachers’ expressed PCK, which was validated by examining artefacts such as lesson plans. As discussed in previous sections, textbooks strongly influence teachers’ decisions concerning what and how to teach (Nicol & Crespo, 2006; Peacock & Gates, 2000; Roth et al., 2006; Tulip & Cook, 1993). Therefore, in addition to The Lesson Preparation Method, an analysis of chemistry textbooks was included to investigate how chemical bonding is presented in textbooks and how they influence teachers’ practice. The first study thus focused on the knowledge of teachers as individuals, but emphasized that their knowledge is influenced by interactions with artefacts such as textbooks. Moreover, the interviews could be seen as situations involving social interaction with the interviewer, during which the teachers might develop new knowledge built on prior knowledge and by reflection. Since the interviews were based on the teachers’ lesson plans, their knowledge was placed in the context of their teaching practice. The results of Study 1 are reported in the first three papers attended in this thesis (papers I-III). A detailed description of the study’s procedures, participants, textbooks, analytical protocols, and so on can be found in the methods sections of the appropriate papers.

The second study, Study 2, focused on the development of teachers’ knowledge, since the results of the first study showed that the teachers generally did not reflect on their teaching practices and that there were few effective connections between the teachers’ knowledge of students’ understanding, representations, and instructional strategies. The results of Study 1 also indicated a gap between previous research findings concerning students’ understanding of chemical bonding models and their representation in textbooks and by teachers. The method used in paper IV was inspired by the learning study framework and a tool for reflection known as content representation, or CoRe. A learning study is a cyclical and collegial process in which researchers and teachers together plan and conduct a lesson, and systematically explore and reflect on their own teaching practice using a stimulated recall approach. This approach is underpinned by the theory of
variation (Marton & Booth, 1997; Runesson, 2005). While this theory was not fully adopted by the teachers participating in the study, it served as an inspiration for their teaching and reflections. The study focused on the development and construction of knowledge in collaboration with others, i.e., interpersonal connections were emphasized as crucial components of the learning process. Since the study involved their actual teaching (as observed in the video-recorded lessons), the study focused on both their expressed PCK (as expressed in the planning of the lessons and the CoRe exercises) and their enacted PCK, as well as the relationship between them. Emphasis was also placed on improving learning processes by relating new knowledge to prior knowledge and experiences, and reflections on experiences and the activities in which a person participates. The result of the second study are reported in paper IV. A detailed description of the study’s procedures, participants, and analysis can be found in the methods section of that paper.

**Figure 8.** An overview of the design of the studies and the corresponding papers, and the types of empirical data collected.
Samples and context

Study 1

The first study was conducted in an upper secondary school context. Ten chemistry teachers (referred to hereafter as T1-T10) from seven upper secondary schools located in Central Sweden volunteered to participate in the project. All of them held degrees qualifying them to teach at upper secondary school chemistry in Sweden, and they had between three and thirty years of teaching experience. No deep personal or work relationships existed between the authors of the paper and the teachers participating in the study.

Chapters concerning chemical bonding (ionic, metallic, and covalent bonds) from five upper secondary level textbooks used by the participating teachers and published by different publishers (referred to hereafter as TB1-TB5) were analysed. All bar one of these textbooks (TB4) are among the most widely used chemistry textbooks. Therefore, their contents can be considered representative of the way chemical bonding is represented in Swedish textbooks.

Study 2

The process involved in a learning study framework is facilitated if the teachers develop trust in each other, so it is advantageous if the participating teachers work at the same school and already know each other. It is also helpful for the time between collegial meetings to be short. As such, the planning and organisation of a learning study exercise will be greatly facilitated by focusing on teachers who work at the same school and in the near vicinity of the researcher’s workplace. Given these facts, it was not considered ideal to continue the involvement of the teachers who participated in the first study. The second study was therefore conducted at the lower secondary level (focusing on teachers whose students are aged 13-15). Three secondary science teachers that had worked together for several years at the same school, located in the neighbourhood of the researcher (Central
Sweden), volunteered to participate in the study. All three teachers hold a degree qualifying them to teach secondary school chemistry in Sweden, and they familiarized themselves with the learning study methodology, variation theory, and CoRe by reading various texts. The students in the participating teachers’ classes that were examined in the learning study were in grades 8 (two classes, 25 and 27 students, respectively) and 9 (one class, 25 students). The study was performed over one semester, and six group discussions were conducted, each with a different focus: conducting CoRe, designing lessons, designing and analysing pre- and post-tests, and analysing and revising the (video-recorded) lessons. Each group discussion last for about three hours. My role as a researcher was to participate in the group discussions to support the teachers during the process, to stimulate their reflections and discussions, and to video-record the lessons. I also contributed by providing insights into science education research and particularly findings concerning students’ understanding of chemical bonding.

**Instruments**

**Semi-structured interviews**

Semi-structured interviews (Cohen et al., 2007; Kvale, 1996) were used in the first study to clarify the teachers’ knowledge of how to teach chemical bonding. Semi-structured interviews are flexible and conducted with a quite open framework that enables face-to-face interaction and two-way communication between the researcher and the informants (Kvale, 1996). They have the potential to provide researchers with rich information, and are commonly used in qualitative research. Major concerns with interviews relate to the interviewer’s skills and experience of interviewing and the lack of standardization (Robson, 2002). Moreover, the informants might tend to give responses that are influenced by their understanding of what is socially accepted and/or likely to please (or provoke) the interviewer (Bryman, 2002).
The questions in the semi-structured interviews used in study 1 were based on research literature on students’ understanding together with brief analyses of the teachers’ lesson plans and the textbooks. An interview guide (see Appendix A in paper II) was used. The questions concerned the teachers’ knowledge of students’ understanding, representations of chemical bonding models and teaching strategies, as well as their motives for choosing specific representations and instructional strategies. The teachers were asked to reflect on their lesson plans and articulate reasons for their instructional decisions. The flexible design of the interviews and open-ended questions offered opportunities to ask follow-up questions and to create questions on the spur of the moment during the interview, giving considerable flexibility to probe for details or discuss issues. The interviews were audio-recorded and transcribed verbatim using the Transana software package, in which the written transcripts are connected to the audio (or video) recording.

**Lesson plans**

In study one, the teachers were individually asked to prepare and submit a lesson plan that was 2–4 pages long including representations and instructional strategies, 1–2 weeks before the interview. No limit was imposed on the kind of sources used for plan preparation, and the teachers had the choice of submitting an already-written lesson plan or writing a new one for the study. The teachers were asked to consider their motives for choosing specific representations and instructional strategies in the lesson plans.

**Stimulated recall and group discussion**

Like interviews, group discussions are widely used in qualitative research. The dialogue in these discussion is generally semi-structured, which allows the participants to express their views about the subject of interest, and the discussion facilitator organises the discussion but usually remains rather passive (Bryman, 2002). The learning study framework used in study two called for group discussions with several
focuses, including the selection of the object of learning, conducting CoRe, designing lessons, pre- and post-test design and analysis exercises, and analysing and revising (video-recorded) lessons. The framework of the learning study and the use of CoRe facilitated and structured the discussions. The researcher in a learning study is to some extent more active than is typical for group discussion facilitators. In group discussions, the participants are stimulated by others’ thoughts and comments (Robson, 2000). Depending on how the discussions develop, the participants may argue or change their opinions. This produces a natural and realistic description of the participants’ thoughts and understanding of the topic (Bryman, 2002). However, the method is more time consuming than individual interviews, and the group dynamics may have significant effects on the expressed thoughts (Bryman, 2002). Therefore, the discussions must be well managed (Robson, 2002). The teachers that participated in study two had worked together for several years at the same school and knew about my background as a chemistry teacher. Moreover, I pointed out that the lesson was “owned” by the group, and emphasized an open climate for thoughts during the discussions.

In the group discussions relating to lesson analysis and revision, a stimulated recall approach was used. This approach has been described as an illuminating and detailed method for eliciting information about teachers’ teaching (Jensen, 2012), and has been used in several studies to facilitates teachers’ learning from their experiences based on respondents’ comments about their work (Davis, 2006; Freitas, Jiménez, & Mellado, 2004; Nilsson, 2008a; Stough, 2001). This approach enables teachers to recollect and comment on their thoughts and decisions during the teaching episode, and these comments on the teaching are usually audio-recorded.

Video recording of the lessons examined in the Lesson Study of study two were used to stimulate the teachers’ reflections on their teaching and remind them of their activities and thinking. They were also used as “evidence” of what actually happened in the class-room and as guides to memory. During the stimulated recall group discussion, the teachers studied the video-recorded lessons together with me as the researcher, and the tape was stopped when the teachers or I wanted to
comment, reflect, or discuss on a special event. The earlier group discussions during which the teachers performed CoRe, designed their lessons, and performed pre- and post-tests had improved their ability to reflect and made them aware of critical aspects of their teaching. As a result, their reflections gradually became more systematic. All the group discussions were audio-recorded and transcribed verbatim using the Transana software, in which the written transcripts are connected to the corresponding audio or video recording.

**Pre- and post-test**

Pre- and post-tests are commonly used in behavioural and social science research to compare groups or effects of interventions (Larsson, 2013). The advantages of using such tests are that they provide an opportunity to use differences between pre- and post-test scores to measure the intervention’s effects (Robson, 2002). Pre- and post-tests were used in the second study to investigate the students’ prior knowledge and existing perceptions, and to provide insight into how the students’ understanding of the content (i.e. the object of learning) and its critical features changed (or did not change) after the lesson. The pre- and post-tests were distributed to the students using computers before and after the lesson, respectively. During the group discussions, the teachers and researcher analysed the pre- and post-tests to reflect on the students’ understanding and the teaching instructions. These discussions were audio-recorded and transcribed verbatim.

**Content representation, CoRe**

As described in the background section, CoRe is a useful tool for making PCK explicit through systematic reflection on teaching practice, and has been used in science education research as well as in teacher education (Abell, 2007). A CoRe is a detailed description of what, how and why a particular content is taught, and was devised by Loughran et al. (2004). In study two, the CoRe was used as a reflection tool to make the teachers’ PCK explicit and to improve the teachers’
systematic reflections. The prompts in the CoRe were discussed by the teachers and me together, and the answers to each prompt in the CoRe were written down during the discussions. Two CoRe exercises were conducted. The first was performed during the first group discussion (CoRe1). This CoRe was then revised after the third lesson (CoRe2), i.e. during the sixth group discussion. These discussions were audio-recorded and transcribed verbatim.

**Qualitative analysis**

The methods for analysing the data collected in both studies were based on qualitative methods. The ability to interpret data and see it from the perspective of the respondents is a key objective of qualitative research (Gibbs & Flick, 2007), and qualitative analysis involves organizing, accounting for and explaining the data (Cohen et al., 2007). Large amounts of data are often collected, and the researcher must decide which data to select for description and further investigation. This commonly involves a combination of deductive and inductive analysis, i.e. an abductive analysis. The data must be categorized or coded to facilitate management and organisation of the information. The initial categorizations are often shaped by the preconstituted research questions, but the researcher should be open to the generation of new meanings from the data. Such openness makes the analysis a reflective interaction between the researcher and the data. Because data handling processes such as transcription involve the transfer of information from one medium to another, they necessarily entail some degree of interpretation. The researcher performing these processes will inevitably have various preconceptions and interests as well as their own background and agenda, which may adversely affect the accuracy of the process (Gibbs, 2007). It is therefore important for the researcher to exercise a great deal of self awareness and caution (Cohen et al., 2007).
Content analysis

Content analysis can be used to examine any form of written material, e.g. interview transcripts and media products, and it is often used to analyse large quantities of text (Cohen et al., 2007). This approach has several advantages: one can observe without being observed; it focuses on meaning in context; is systematic and verifiable because the rules for analysis are explicit, transparent and public; and it can be verified by reanalysis and replication because the data are recorded in a permanent form (texts) (Cohen et al., 2007). Content analysis involves several steps: coding, categorizing, comparing categories and making links between them, and finally drawing conclusions from the text (Cohen et al., 2007). According to Cohen et al. (2007), the creation of categories involves placing the units of analysis into meaningful groups, i.e. categories. Among other things, a category may include subject matter; how a matter is treated (positively or negatively); values; goals; methods used to achieve goals; traits; conflicts (sources and levels); and endings (how conflicts are resolved). Interpretative notes are often appended to the categories. A unit of analysis is a datum that the researcher considers important and which has meaning in itself; examples include words, phrases, sentences, paragraphs, whole texts, people, or themes.

In both studies, the audio-recorded interviews and group discussions were transcribed in their entirety. All participants were also anonymized to ensure confidentiality. Abductive content analysis was used in both studies to analyse the interviews, textbooks and group discussions. In study one, the abductive content analysis was used to investigate representations used in textbooks and by teachers, as well as teachers’ knowledge of students’ understanding and instructional strategies. The categories for analysing the representations were based on a literature review of reports on students’ understanding and data from textbook chapters on chemical bonding. In study 2, an abductive content analysis was used to identify themes and changes in the ways the teachers reflected on their teaching where the components of PCK interact within the teachers’ reflections. Initially, the components of PCK and CoRe prompts were used to create categories. The analysis then continued with a focus on identifying themes in the ways that the
teachers changed and developed handling and organizing of content to promote students’ learning. The analysis of the interviews and group discussions was performed using the Transana software package, in which the written transcripts are connected to the corresponding audio (or video) recording. This facilitates the creation of units, categorization, coding, and making interpretative notes. For further details of the qualitative analysis in the studies, see the methods sections of the appropriate papers.

**Discussion of methods**

The worth of any piece of research must be assessed, regardless of whether it uses quantitative or qualitative approaches. Qualitative research can be described as the study of the empirical world from the perspective of the person being studied (Krefting, 1991), and the ability to interpret the data and see it from the point of view of the participants is a key objective of qualitative research (Gibbs, 2007). Behaviour is influenced by physical, sociocultural, psychological, and environmental factors, and many of these factors (as well as many aspects of behaviour) are not observable by the researcher (Krefting, 1991). Therefore, subjective meanings and perceptions of the subject are considered critical in qualitative research. Moreover, because the researcher is intimately involved in the research and is an important part of the research process as well as a part of the researched world, they cannot be completely objective in their analysis (Gibbs, 2007; Cohen et al., 2007). The data are descriptive and often analysed inductively rather than using categories defined *a priori* (Cohen et al., 2007). Since the nature and purpose of quantitative and qualitative research are different, it can be argued that models used to evaluate quantitative research are seldom relevant to qualitative research (Krefting, 1991). Further, not all qualitative research can be assessed with the same strategies because many dissimilar approaches with different methods and purposes are used (Krefting, 1991). Therefore, it is important to select a method of evaluation that is appropriate for qualitative research but still ensures rigor and does not sacrifice either the relevance of qualitative data (e.g. Krefting, 1991) or the different meanings and aspects of concepts such as validity (Kvale, 1996). In the
following sections, I discuss different kinds of validity as presented by Kvale (1996) and aspects of trustworthiness according to Krefting (1991), which I see as central to this work. I also show how my research relates to these aspects.

Validity

The types of validity I consider central to this work are *pragmatic validity*, *communicative validity* and *inter-subjective validity*. According to Kvale (1996), pragmatic validity is based on observations and interpretations, and is based on the application rather than the justification of knowledge. That is to say, it relates to the extent to which a knowledge statement is accompanied by action or instigates changes of actions, i.e. the extent to which the research outcomes can be considered useful. The research design, methods, and results of this thesis imply that the research is applicable to teaching practice and teachers’ professional development. During study two, the teachers’ reflections resulted in changes in their teaching practices, which were identified in the video-recorded lessons. Communicative validity concerns the researcher’s ability to argue convincingly for their interpretations and the relevance of those interpretations. While the researcher is not searching for the “right” interpretation, their interpretation must be defensible. A related concept is intersubjective validity, which relates to how the research was reviewed and critized while being conducted, and the academic status of those who discussed the research. The methods and interpretations used in the study must be accepted as appropriate by the research community; such acceptance can be obtained by participation in research seminars, conferences and by publishing results in peer reviewed journals. The validity of my research in terms of peer evaluation and these three concepts is discussed below.

Trustworthiness

Krefting (1991) summarized and interpreted Guba’s (1981) model for assessing trustworthiness, which is based on four factors that are
relevant to both quantitative and qualitative research: *truth value, applicability, consistency, and neutrality*. In qualitative research, truth value can be assessed in terms of *credibility* (which corresponds to internal validity in quantitative research). Applicability can be assessed in terms of *transferability* (or external validity in quantitative research), consistency is assessed in terms of *dependability* (reliability in quantitative research), and neutrality is assessed in terms of *confirmability* (objectivity in quantitative research) (Table 3). These four aspects of trustworthiness are further described below, along with the strategies used to maximise them in the works presented in this thesis (Table 3).

**Table 3.** Comparison of aspects of trustworthiness between research approaches, and strategies to increase each criterion relevant for this thesis.

<table>
<thead>
<tr>
<th>Criterion relevant for</th>
<th>Aspects</th>
<th>Qualitative approach</th>
<th>Quantitative approach</th>
<th>Strategies to increase each criterion relevant for this thesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truth value</td>
<td>Credibility</td>
<td>Internal validity</td>
<td></td>
<td>Prolonged engagement</td>
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<td></td>
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<td>Reflexivity</td>
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<td>Peer examination</td>
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<td>Triangulation</td>
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<td>Interview technique</td>
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<td></td>
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<td></td>
<td></td>
<td>Establishing authority of researcher</td>
</tr>
<tr>
<td>Applicability</td>
<td>Transferability</td>
<td>External validity</td>
<td></td>
<td>Dense description of the participants and research contexts</td>
</tr>
<tr>
<td>Consistency</td>
<td>Dependability</td>
<td>Reliability</td>
<td></td>
<td>Dense description of research methods</td>
</tr>
<tr>
<td>Neutrality</td>
<td>Confirmability</td>
<td>Objectivity</td>
<td></td>
<td>Triangulation</td>
</tr>
</tbody>
</table>

*Strategies to increase truth value*

The first aspect of trustworthiness, *truth value*, relates to the researcher’s confidence in the truth of the findings based on the design, participants, and context. In qualitative research, truth value is obtained from the disclosure of human experiences as they are lived and perceived by the participants, is subject-oriented, and can be assessed in terms of *credibility*. Strategies for increasing credibility
that are relevant to this work include prolonged engagement, reflexivity, peer examination, triangulation, interview technique, and establishing the researcher's authority. Reflexivity can also be seen as an aspect of validity (Cohen et al., 2007), along with neutrality (commonly assessed in terms of confirmability) (Krefting, 1991). Prolonged engagement concerns the ability to identifying recurrent features, e.g. patterns, themes, and values. The recommended way of achieving this is to spend enough time with the study participants to permit the gathering of more sensitive information. The relationship between the researcher and the participants determines the quality and quantity of the collected information (Cole, 1991). In study 2, I participated in the group meetings, which collectively comprised over twenty hours of discussion and reflection. It is important for participants to trust and feel safe with the researchers so that they will be prepared to share their experiences and thoughts. To achieve this, I explained that my intention was to listen to their thoughts and experiences, and that I did not aim to assess their teaching. During both studies, I tried to be an active and interested listener, and not to evaluate their thoughts and reflections, and to create an open atmosphere in the interviews (study 1) and group discussions (study 2). Further, the teachers were assured of their right to withdraw from the interviews or group discussions at any time, and that their data would be held in confidence. My background as a teacher might also have helped them to feel more relaxed rather and to see me as someone other than a researcher who would not necessarily understand their practice. My background may also have helped me to recognize important points when collecting and analysing data. It should be noted that such closeness between the researcher and the participants may also influence the participants. Therefore, reflexivity is important. Reflexivity refers to the recognition of the influence of the researcher’s own background, perceptions, and interests on the research process (Krefting, 1991). Because the researcher is a part of the real world they are investigating, these effects cannot be eliminated, so they must be recognized, reflected on, and their potential contribution to or effects on the results must be acknowledged (Cohen et al., 2007). The researcher might have multiple roles in the research (Krefting, 1991) – for example, I am both a researcher and a teacher. Throughout the research process, I have tried to be aware of how my background as a
teacher could influence the design, data collection and analysis of the data, which has stimulated my reflexivity, i.e. my recognition of how my background as a teacher could create a pattern of thoughts that might impact the evaluation of the research object. This was emphasized at the very beginning of my research studies, when I took courses in the Swedish national research school of science, technology and mathematical education.

Peer examination involves the researcher’s discussions of the research process and findings with impartial colleagues who are experienced with qualitative methods (Krefting, 1991). This may involve checking of categories developed from the data. Peer examination can also serve as a strategy for increasing communicative validity and inter-subjective validity (Kvale, 1996). The methods and results outlined in this thesis have been discussed and presented at research seminars and conferences. Moreover, the analytical processes, development of categories and interpretation of results has been discussed with the co-authors of the papers included in this thesis, three of them professors of science education and one senior lecturer. In this context, it should be noted that the analytical framework used in study 1 to analyse representations of chemical bonding models was based on findings from several earlier studies on students’ difficulties understanding models in general and models of chemical bonding, which have been recognized for several years. Additionally, papers I-III have been published in peer reviewed journals.

Triangulation means providing several different pieces of data, which are assessed against each other to enable cross-checking and interpretation (Krefting, 1991). One type of triangulation is triangulation of data methods, where data collected by various means are compared (e.g. interviews, participant observations, and life histories). In this thesis, study one involves data from the teachers’ lesson plans, individual interviews and their textbooks. In study two, data were collected from group discussions, CoRe exercises, and video-recorded lessons.

Interview technique concerns issues such as reframing and repetition of questions, and the questions’ internal consistency (i.e. the questions’
logical rationale and the extent to which they bear on the same topic). The interviews in study one were conducted following an interview guide outlined by the researchers (i.e. the authors of paper I) together, and questions were consistently followed up on and reframed where necessary.

!*Establishing the researcher’s authority* concerns the unique authority of the researcher, who is regarded as a measurement tool for this purpose (Krefting, 1991). Relevant characteristics include the researcher’s familiarity with the phenomena under investigation and the setting of the study; a strong interest in conceptual or theoretical knowledge; good investigative skills developed through literature reviews, completion of relevant course work, and experience in qualitative research methods. Given my background as as a teacher, I consider myself familiar with teaching practice as well as the topic examined in this research. As a PhD student, I am not an experienced researcher, but I have completed methodology courses and reviewed literature in the field.

*Strategies to increase applicability*

The second aspect of trustworthiness, *applicability*, refers to the degree to which the findings can be applied to other contexts or groups, i.e., the ability to generalize from the studied sample to larger populations (Krefting, 1991). The ability to generalize is irrelevant in many qualitative research studies because their purpose is to describe some phenomenon rather than generalize. Therefore, applicability in qualitative research can instead be assessed in terms of *transferability* (which corresponds to external validity in quantitative research) (Krefting, 1991). This criterion is satisfied if the findings can be fitted into sufficiently similar contexts outside of the study. Transferability can be seen as the responsibility of the reader rather than the researcher provided that the researcher has presented sufficient descriptive data to enable meaningful comparison. A key factor in the transferability of the data is the representativeness of the participants. Therefore, it is important that the researcher provide dense background information about the participants and the research contexts. This allows others to
assess the transferability of the findings. In this thesis and attended papers, I have tried to give a detailed description of the studies’ contexts as well as the teachers and textbooks that were involved.

**Strategies to increase consistency**

The third aspect of trustworthiness, *consistency*, concerns the likelihood of obtaining the same findings if the research were repeated with the same subjects or in a similar context (Krefting, 1991). In qualitative research, this aspect is assessed in terms of the *dependability* criterion (reliability in quantitative research). In qualitative research, the key is to learn from the participants rather than controlling them. Therefore, the researcher and the participants are the instruments that should be assessed for consistency. Variability is expected in qualitative research, and this variability can be ascribed to identified sources. Relevant strategies for satisfying this criterion in the context of this work include *dense descriptions of research methods, triangulation, and peer examination*. The latter is described and discussed above, and the former relate to accurate and detailed descriptions of the methods used for data gathering, analysis, and interpretation, which I have tried to provide in this thesis and the appended papers.

**Strategies to increase neutrality**

The fourth aspect of trustworthiness, *neutrality*, concerns the absence of bias in the research procedures and results (Krefting, 1991). In qualitative research, this aspect is assessed in terms of *confirmability* (objectivity in quantitative research). To achieve conformability, truth value and applicability must be established. The worth of the findings can be increased by reducing the distance between the researcher and the participants. Therefore, the focus shifts from the researcher to the data. Relevant strategies for satisfying this criterion in this research include triangulation and reflexivity, which are discussed above.
Ethical considerations

In educational research, there are several standard ethical guidelines regarding the treatment of participants. For instance, the participants should be informed about exactly what will happen, how the material will be used and handled after the study, and what type of data that will be collected. Moreover, it is important that the participants are aware of that participation is voluntary (Gibbs & Flick, 2007) and that they have the right to withdraw their participation at any time (Robson, 2002). Moreover, they must be ensured that their data will be handled in confidence (Robson, 2002), and of the anonymization of transcripts (Gibbs & Flick, 2007).

In both studies included in this thesis, I followed these standard ethical guidelines. All participating teachers and students (and the students’ parents) completed a written consent form prior to the data collection. The teachers were also asked for permission to quote them or use their representations of models from the lesson plans (study one) and observations of their lesson planning (study two) in research contexts such as seminars, conferences and papers, then guaranteed individual confidentiality and anonymity. Ethical standards were also followed regarding the reporting of the research, particularly with respect to issues such as mirepresentation, plagiarism and assistance of uncredited others (Robson, 2002).

In study two, the framework of a learning study was used, which can be challenging for teachers. They must be able to share tensions and dilemmas from their personal teaching experience, and to speak honestly and personally. Therefore, the participating teachers must develop trust in each other. This made it advantageous that the participating teachers worked at the same school and already knew each other. I tried to create an atmosphere of trust in the group by pointing out that the lessons were collegial and “owned” by all the teachers. Moreover, I made it clear that the individual teaching would not be assessed in terms of ‘good or bad’ teaching. This approach was also adopted during the interviews from study one. In addition, there is a risk that teachers and students may feel anxiety about video- and audio-recorded material being shared with others. Therefore, I
informed the teachers and students that only I and my supervisors would have access to the material. While the participating teachers analysed the video-recorded lessons, the purpose was only to reflect on their teaching, not to assess or grade the students. Therefore, the students were informed that the video-recorded lessons and pre- and post-test would be used to support the teachers’ reflections (and research analysis) only, to avoid inducing anxiety that the test or lesson might be used to assess their knowledge or grade them. However, it is important to consider the impact that the video-recording might have on the participants.

In a learning study the teachers’ awareness of factors that make a difference in student learning is improved through systematic reflection. Participation in a learning study can thus contribute to the development of teachers’ knowledge of relationships between content to be taught and students’ learning, and offers an opportunity to develop knowledge of the conditions necessary for students’ learning. Moreover, in the study, teachers were given opportunities to engage in systematic collegial reflection and to share teaching experiences. If teachers’ PCK is developed, it can be assumed to benefit the students’ learning. Moreover, the results of this study will benefit research on teachers’ PCK, in-service as well as pre-service teachers, and teacher education. Therefore, I consider the benefits of enhanced knowledge to exceed the risks to the participating teachers and students.
Results – summary of papers

Paper I, II, and III

The results of papers I-III are summarized together since they are based on data from the same study and collectively provide insights into how chemical bonding is presented in textbooks and by teachers, and how the textbooks might influence teachers’ knowledge of this topic.

The first paper aimed to explore how chemical bonding models are represented in chemistry textbooks used at the upper secondary level, and to relate these representation to research findings concerning students’ understanding. This exploration revealed that representations that can give rise to alternative conceptions and difficulties understanding chemical bonding were heavily used in all of the studied textbooks. Almost every textbook contained at least one example of every type of representation that had been identified as a source of students’ difficulties in understanding; the sole exception was one book that lacked one specific category of problematic representation (while still having examples of every other category).

Paper II also explored the representation of chemical bonding models, but focused on their representation by teachers rather than textbooks. The results reported in this paper showed that the participating teachers also used representations that could give rise to alternative conceptions and difficulties understanding chemical bonding. Moreover, they seemed to be generally unaware of how representations could contribute to students’ difficulties in understanding. The aim of paper III was to investigate how textbooks influence teachers’ selection and use of representations, and how this in turn relates to students’ difficulties understanding. By analysing the sequence and manner in which different models and concepts are presented in textbooks, and drawing correlations with the sequence and manner in which these topics are discussed by teachers, I found that there is a strong correlation between how chemical bonding models are presented in textbooks and by teachers. Specifically, there was considerable coherence with respect to (a) the sequence in which different types of
bonding were introduced, (b) the examples used to illustrate various points, and (c) how chemical bonding models were represented.

Each paper contains a detailed description of how the representations used in textbooks and by teachers can cause difficulties understanding; these descriptions are briefly summarized below. All the textbooks used the traditional approach that divides chemical bonds into two main categories: \textit{intra-molecular bonding} (ionic, covalent, and metallic bonding) and \textit{intermolecular bonding} (i.e. bonding between molecules). The different types of bonding were thus presented separately and as distinct concepts. Both textbooks and teachers then introduced each type of bonding in the same order: first ionic, then covalent, polar covalent, and metallic bonding. One textbook (and a teacher who used this textbook) adopted a slightly different sequence in which metallic bonding was presented first, followed by ionic, covalent, and polar covalent bonding. All the textbooks and teachers started with discrete covalent molecules before presenting giant covalent lattices such as diamond and graphite. This sequence might cause students to attempt to conceptualize all chemical structures in terms of molecules. Taber and Coll (2002) suggest teaching metallic bonding first, followed by ionic bonding, then covalent bonding, and to start with giant covalent lattices before presenting discrete covalent molecules. Alternatively, Levy Nahum et al. (2008) suggest presenting chemical bonding as a continuum of related concepts rather than different types of bonding, and to start with basic principles before concluding with specific examples.

All the textbooks and teachers focused on individual atoms when presenting ionic, covalent, and polar covalent bonding (Table 2, category 2). They thus introduced ionic bonding in terms of electron transfer by presenting the formation of ions constituting the ionic compound (Table 2, category 5a), and covalent and polar covalent bonding were introduced by presenting the formation of molecules and electron sharing (Table 2, category 5b). That is, they introduced these types of bonding using a hypothetical, fictional account of its origin that frames bonding in terms of interactions between individual atoms, when the reactants actually consist of molecules or have a lattice structure. All the textbooks and teachers made extensive use of the
octet rule and focused on electronic configurations (Table 2, category 1) to explain all types of chemical bonding other than metallic bonding. In fact, the octet rule was used explicitly or implicitly as a reason for bonding (Table 2, category 3a). Anthropomorphic descriptions were also common and used in many ways, both in textbooks and by teachers (Table 2, category 4). For example, atoms were said to fight or hunger for electrons, to not share electrons fairly or share as brothers would, to like electrons, to be able to feel electrons around them, to be pleased, or to be jealous.

All the textbooks and teachers also used representations that describe chemical bonding in terms of electrostatic forces, although this presentation was offered alongside the octet rule and the phrase “electrostatic forces” was seldom used (Table 2, category 6). Ionic bonding was the type of bonding that was most frequently attributed to electrostatic forces, although the electrostatic interactions were presented as resulting from the transfer of electrons between atoms (i.e. ion formation) driven by the octet rule. There were few representations of covalent, polar covalent, or metallic bonding that were framed in terms of electrostatic forces. None of the textbooks or teachers used the term “electrostatic force” or “attraction force”. Notably, only one textbook and two teachers explicitly mentioned that all types of bonding stem from attractions between ‘positive and negative’ charges. Both of the teachers who chose this representation used this textbook. In contrast, two textbooks introduced chemical bonding explicitly in terms of atoms striving to attain a noble gas shell. I identified only two non-verbal representations of chemical bonds being formed because of electrostatic forces: one related to covalent bonding and was found in one of the teachers’ lesson plans, and the other related to ionic bonding and was found in a textbook (Table 2, category 6a). None of the textbooks or teachers explicitly mentioned attaining a lower energy or increased stability as a reason for bonding; bond formation was primarily attributed to the attainment of a noble gas structure. As one teacher put it, “I try to explain that [the atoms] want to attain a noble gas structure and that once they have attained that structure, they reach a lower energy level and become more stable”. These representations collectively could cause students to generate the octet framework, which would then reinforce other
alternative conceptions and difficulties in understanding chemical bonding (Taber & Coll, 2002).

I also identified examples of hybrid models, which were primarily used to teach covalent and polar covalent bonding (Table 2, category 7). None of the textbooks or teachers mentioned the original models from which the individual elements of the hybrid models were derived. Moreover, the nature and purpose of models were rarely discussed. It is claimed that hybrid models can give rise to difficulties in both teaching and learning (e.g. Gericke & Hagberg, 2007; Justi & Gilbert, 2000). Additionally, it is widely accepted that to overcome the difficulties associated with the use of models, it is important for students to recognize the functions and limitations of models, and to understand that a concept or phenomenon can often be explained by several different models.

The results of papers I-III clearly show that representations that can give rise to alternative conceptions and difficulties understanding chemical bonding are widely used in current textbooks and by teachers, and that the textbooks influence teachers’ decisions about how to represent chemical bonding. These papers together indicate that there is a gap between the findings of science education research on the one hand, and teaching practice and the content of textbooks on the other. I argue that these results clearly demonstrate that this gap should be bridged.

Paper II also aimed to investigate the teachers’ knowledge of students’ understanding and instructional strategies in the context of chemical bonding. The results presented in this paper show that all but one of the teachers considered chemical bonding a topic that students find hard to understand, and several examples of students’ alternative conceptions and difficulties were mentioned. Most of the examples given by the teachers were resembled examples found in the literature. However, less than half of the examples found in the literature were mentioned by the teachers. Moreover, on several occasions, the teachers were unable to specify students’ difficulties and hesitated when trying, even though they could sometimes provide examples after
some reflection. These results illustrate that the teachers’ knowledge of students’ understanding can be improved.

Finally, the results of paper II show that the teachers’ repositories of instructional strategies could be enlarged. For example, most of the instructional strategies used by the teachers were neither subject- nor topic-specific. In addition, the strategies used to ascertain students’ understanding were not actually adequate to determine whether all the students understood the topic, which is a problem because it is not possible to evaluate the effectiveness of strategies for improving students’ understanding without being able to reliably assess that understanding. Although the teachers were aware that many students found chemical bonding challenging, few of them explicitly discussed selecting specific representations or instructional strategies in order to improve students’ understanding. The results also show that teachers do not appear to reflect frequently on their teaching practices. Several teachers described the study’s interview as one of few occasions in several years when they had discussed and reflected on their teaching. Such reflections were considered important by the teachers, but they seldom have time to complete them. Effective teaching requires knowledge of students’ understanding, representations, and instructional strategies, all of which must be integrated to improve students’ understanding of the topic at hand (Park & Chen, 2012). The results presented in papers I-III show that there is a need to strengthen teachers’ grasp of these individual components of PCK, and to strengthen their integration.

**Paper IV**

The focus in this paper was on the development of teachers’ knowledge of teaching chemical bonding. Its aim was to investigate how interventions based on methods such as a learning study and Content Representations (CoRe) might enhance teachers’ reflections and PCK. The results clearly showed that the interventions prompted the participating teachers to change the way they handle and organize lesson content to promote students’ learning. These changes evolved as the teachers made connections between the individual components of
their PCK, which also led to the development of the individual components. Specifically, the teachers a) changed how they structured the content of the lessons and framed the lesson activities, b) changed their representations of chemical bonding models and the examples they used, c) become more aware of students’ understanding and how they learn, d) became more capable of motivating their actions and choices of content and strategies, and e) developed their content knowledge.

As the study progressed and the teachers reflected, the structure and content of their lessons (and the activities planned for those lessons) evolved, and the teachers became more able to support their choices with reasoned arguments, and they began to consistently take students’ understanding into consideration during their reflections. They also started asking themselves why-questions more frequently (e.g. “why am I using this specific structure, content, or activity?”), and developed their ability to motivate and justify their answers to these questions. That is, the individual components of their PCK became increasingly well-integrated with one-another. They also developed new strategies for verifying students’ understanding: after the first lesson, at the beginning of the study, they relied exclusively on post-tests, whereas by the end of the third lesson they had developed a strategy based on concept maps. Moreover, they changed their attitudes to certain activities/instructional strategies. For instance, in the group discussion where the first lesson was planned, one of the teachers was sceptical about having the whole class do practical laboratory work. However, during the last group discussion, that teacher said that he now felt more positive about such activities and would use them more often.

Over the course of the study, the teachers changed their representations of chemical bonding models in several ways. In the first group discussion, I presented a teaching model based on chemistry education research findings that emphasizes the role of electrostatic interactions in all forms of bonding. During the group discussions, the teachers recognized the benefits of this model and agreed to adopt it. However, to fully adapt this teaching model, they needed to reflect upon it at length and be reminded that electrostatic interactions can be used to describe and explain all types of bonding.
Sharing recent research results with the teachers also improved their awareness of how representations can affect students’ understanding. As a result, the teachers recognized that they needed to change and develop their representations. Connections were thus created between their knowledge of representations and their students’ understanding. This process had a particularly strong effect on the development of the teachers’ representations of metallic bonding. In addition, the teachers reflected on the need for additional models and presentations in different modes, as well as the importance of using specific examples or words, and the potential effects of these factors on students’ understanding.

During the process, the teachers became more aware of their students’ lack of prior knowledge. In addition, they became better able to specify their students’ difficulties. When the first CoRe exercise was conducted, they said it was difficult for students to understand concepts in general terms, but during the second CoRe exercise, they could specify what concepts the students found problematic, and in what way, enabling them to reflect more comprehensively. A comparison of the results and discussions during the CoRe1 and 2 exercises also clearly showed that the teachers had improved their ability to motivate and justify their choices. Paper IV thus shows how systematic collegial reflections conducted using the learning study and CoRe approaches can enhance the development of individual components of teachers’ PCK and also improve their cohesiveness, leading to a more robust overall structure. In addition, it showcases a practical way of integrating research findings into teaching practice, and thereby reducing the gap between research and practice.
Discussion

The four papers included in this thesis together provide new insights into the teaching of chemical bonding and its learning by both teachers and students. Several aspects of the teaching and learning of chemical bonding were explored; textbooks, students’ understanding, and teachers’ professional knowledge. Despite the existence of several studies on students’ difficulties understanding chemical bonding models and the sources of these difficulties, the results show that many textbooks and teachers use representations that have been linked to such difficulties. There is thus a gap between research results and teaching practice. Consequently, to improve students’ understanding, it will be necessary to change the ways chemical bonding is represented in textbooks and taught by teachers. This will contribute to the development of both teachers’ and students’ learning, and the improvement of teachers’ teaching practices, leading to better student learning. In this chapter, I first discuss the need to change current representations of chemical bonding and then discuss how some alternative approaches to presenting this topic, that have been suggested on the basis of science education research, can reduce students’ difficulties in understanding. I also discuss ways of understanding chemical bonding at the upper and lower secondary levels, and show how the learning study approach and CoRe can be used to incorporate research findings into teachers’ teaching practice and improve their professional learning, leading to changes in their practice. Finally, the implications of this thesis are discussed and some suggestions for future research are presented.

Changing the representation of chemical bonding models

The role of textbooks

There are no extensive empirical knowledge bases of students’ alternative conceptions and difficulties in understanding for most academic topics (Smith & Banilower, 2015). However, as described in the preceding sections, such a knowledge base does exist for chemical
bonding. Despite the availability of this knowledge base, every textbook I examined relied heavily on representations that research had shown to be associated with difficulties in understanding. Such representations were also used extensively by the participating teachers. This indicates that there is a substantial gap between the findings of science education research and teaching practice. Consequently, the representations used in textbooks and by teachers might contribute to students’ alternative conceptions and difficulties in understanding. I also demonstrated that there is a strong correlation between how chemical bonding models are presented in textbooks and by teachers. This finding is consistent with previous studies showing that textbooks strongly influence teachers’ decisions concerning what and how to teach (Nicol and Crespo 2006; Peacock and Gates 2000; Roth et al. 2006; Tulip and Cook 1993). This suggests that students’ alternative conceptions may persist if textbooks present chemical bonding in such ways, and if teachers continue to use those textbooks as references for lesson planning. Similar conclusions have previously been drawn for other topics in science education (Eilks, Witteck, and Pietzner 2012; Gericke and Hagberg 2010). Moreover, several studies have shown that teachers strongly influence students’ learning (Justi and Gilbert 2002; Yoon et al. 2007). These circumstances make the influence of textbooks on teachers’ practices problematic.

However, the influence of textbooks on teachers’ practices can also be seen as an opportunity rather than a problem. Because textbooks provide the most detailed representations of curricula (Mikk, 2000) and serve as curriculum guides that help teachers decide what and how to teach (Nicol & Crespo, 2006), this influence could be exploited to ease the implementation of new curricula and to provide teachers with better representations and explanations that strengthen students’ understanding of scientific concepts. Therefore, it is important that the representations used in textbooks be updated on the basis of the most recent findings from science education research. This means that there is a need for effective ways of incorporating research results into the practice of writing textbooks. Because textbook authors often have a background as teachers, incorporating research into teachers’ practice can be one way to achieve this. These issues must also be addressed through politics: writing textbooks for secondary school students
should be seen as important and valuable academic work, which is not the case at present (at least in Sweden). Incentives for researchers to write or contribute knowledge to textbooks should therefore be discussed.

In my opinion, the acquisition of good textbooks alone will not be enough to improve teachers’ and students’ learning. This is because while textbooks remain one of the most important information sources used by teachers during lesson planning, the internet and modern information and communication technology provide access to new tools and sources that are becoming increasingly influential. No matter what tools teachers use to guide their teaching, they must be aware of how specific representations can contribute to students’ difficulties understanding, and continuously analyse their tools to see if they could be improved. This could be facilitated by actively familiarizing teachers with relevant research findings and encouraging them to incorporate such findings into their teaching practice. Even if the textbooks are updated according to research findings, the incorporation of those findings into teaching practice will be most effective if teachers are encouraged to reflect on their students’ understanding so that they recognize the advantages of the new approach and connect their reflections to their experiences. Having reflected in this way, they will be well placed to select appropriate representations or activities to enhance their students’ learning (Vickström, 2014). It is considered important that teachers reflect on their practice collaboratively with colleagues in order to develop the individual components of their PCK and the connections between them (Gess-Newsome, 2015; Park & Oliver, 2008). This again indicates that merely acquiring better textbooks will not be enough to adequately support teachers’ professional learning. Paper IV of this thesis describes one way of performing such collaborative reflection using the learning study approach and CoRe. During that work, I shared my knowledge of research findings with the participating teachers. In addition, teachers’ ability to think critically about their choices of textbooks and other teaching tools will be greatly strengthened if they regularly refresh their knowledge of their subject at a higher level than that taught in secondary school textbooks. For example, secondary school teachers might benefit from refreshing their knowledge of the more advanced
models of chemical bonding that are taught at university level. This could increase their awareness of the use of hybrid models, and their ability to critique the models presented in secondary school textbooks.

New frameworks for presenting chemical bonding

As discussed in previous sections, traditional approaches to teaching chemical bonding can contribute to students’ difficulties in understanding. One might therefore be tempted to ask why chemical bonding is taught using these approaches despite research findings showing that they can cause students to have difficulties in understanding, and the availability of the models based on the theory of quantum mechanics. As noted by Levy Nahum et al. (2008), shortly after the formulation of this theory, Dirac in 1929 stated that: “The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known.”

According to Levy Nahum et al. (2008), there are two reasons for the failure to incorporate modern models of bonding into textbooks. The first reason is historical: chemistry initially developed through the collection of empirical observations, which chemists sought to put in order using various systems of classification. Bonding models emerged as a natural attempt to rationalize these classifications. As new and refined bonding models were developed, they were simply added to the existing ones in many textbooks. However, the historical perspective is not necessarily the most appropriate one for teaching. The second reason is that the traditional approach provides clear-cut definitions that facilitate explanations and provide a “sense of security” for the students. Moreover, it allows for straightforward evaluation of students’ learning based on clear-cut answers to well-defined questions. However, this is may come at the cost of over-simplification and over-generalisation, which have been shown to impede learning.

The background chapter of this thesis describes two new frameworks and teaching models that have recently been suggested to reduce students’ difficulties in understanding chemical bonding. Both of these
frameworks are designed to answer a question that puzzles many students, namely “what exactly is it that causes particles to interact and form a chemical bond?” However, these frameworks must be evaluated by considering how chemical bonding is intended to be understood by the students. At the lower secondary level, I believe that it is sufficient for students to realize that all substances consist of individual atoms (e.g. metals or substances such as diamond), ions or molecules, that there exist forces that hold these particles together, and that these forces are disrupted in chemical processes, which requires energy. The forces could be explained in terms of the teaching model suggested by Taber and Coll (2002) and Lee and Cheng (2014), which is based on the contribution of electrostatic forces to all kinds of bonds. This model makes it clear that the same force is responsible for holding together the constituent particles of every substance, no matter what its composition. Bonding is thus introduced as an electrical concept, and all forms of bonding are treated on an equal footing. Conversely, traditional approaches present different types of bonding as being wholly different, using different models. I also suggest that lower secondary school students should have a basic understanding of the relationship between chemical bonding and the properties of materials. For example, they should be aware that a substance’s physical properties (e.g. its boiling and melting points, brittleness, hardness, electrical conductivity, and so on) depend on its structure and the strength of the forces between its constituent particles. Taber and Coll (2002) also suggest that the first kinds of structures to be introduced when teaching bonding should be ionic, metallic and molecular lattices, and that the discussion should focus on physical principles. They argue that this will avoid the emphasis on atoms and electronic configuration that can cause students to generate alternative conceptual framework such as the octet framework. I agree with these authors’ claim that their teaching model provides an optimal level of simplification, that is, sufficient scientific correct and will give students an adequate understanding of chemical bonding at the lower secondary level. Importantly, it also provides a robust foundation for those students who will go on to study chemistry at higher levels of education, and is consistent with the more sophisticated chemical bonding models based on quantum mechanics that they will encounter at university
level, or the bottom-up framework that may be used by teachers at the upper secondary level.

In contrast to the framework proposed by Taber and Coll (2002), the bottom-up framework suggested by Levy Nahum et al. (2008) is grounded in quantum mechanics, but still treats all chemical bonds on an equal footing. In this framework, chemical bonding is introduced using a continuum of related concepts rather than by discussing different types of bonding. Key concepts are energy, forces, and the relationships between them, and the idea that stability is obtained by minimizing energy. I consider this framework appropriate for use at the upper secondary level, where chemical bonding is a central topic and its impact on the occurrence and properties of materials must be understood. These issues are defined as core content in the new Swedish curriculum for chemistry at the upper secondary level (Swedish National Agency for Education, 2011a). I consider it appropriate for chemical bonding to be understood in terms of a continuum of related concepts instead of different types of bonding. This framework builds from basic principles, concludes by discussing specific properties, and explores the relationships between bonding, structure and properties, which are key issues in chemistry. As such, it links macro- and microscopic properties and phenomena in a logical way.

Like the framework of Taber and Coll (2002), which emphasizes electrostatic forces, the bottom-up framework presents chemical bonding as a consequence of Coulomb’s law (the physical law that describes the forces acting between static electrically charged particles), but places additional emphasis on the relationship between Coulomb’s law and stability in terms of the balance of attractive and repulsive Coulomb potential energies as well as the kinetic energy of the electrons. The traditional categories of chemical bonding are used, but are presented as extremes on various continuous scales, and the continuum of bonding is related to a continuum of bond strengths. However, Levy Nahum et al. (2008) claim that models based on Coulomb’s law alone are insufficient, and that some discussion of quantum theory is needed because an electron orbiting a nucleus does not really behave like a moon orbiting a planet (an analogy that is
commonly used when discussing atomic structure). The authors claim that understanding electrons requires consideration of their wave-like character, and therefore recommend that electrons in atoms should be described as “probability clouds” of negative charge surrounding the nucleus, i.e. orbitals.

According to Levy Nahum et al. (2008), the advantages of the bottom-up framework are that introducing chemical bonds in terms of continuums removes the artificial division between different types of bonding. Moreover, there is no dichotomous classification in terms of fully transferred electrons (ionic bonds) and shared electrons (covalent bonds), and over-simplifications and over-generalizations are avoided. Like Taber and Coll (2002), the authors claim that this framework prevents pedagogical impediments to further study, and helps students to recognize that molecular species and bonding scenarios that textbooks often designate as “exceptions” can be understood using the same few principles used to rationalize the “regular cases”.

One potential disadvantage of the bottom-up framework is that its reliance on relatively abstract concepts may be too demanding for some students. This issue was noted by Levy Nahum et al. (2008). Another issue is that this framework presents ionic bonding in terms of a charge transfer that generates positive and negative ions, which are then attracted to one-another as a consequence of Coulomb’s law. The presentation of ionic bonding in terms of electron transfer might cause students to identify ionic bonding with electron transfer instead of electrostatic forces (Robinson, 1998; Taber, 1997; Taber & Coll, 2002). If ionic bonding is presented as a charge transfer, one must emphasize that ionic bonds can also be formed between pre-existing ions, as occurs when a solid ionic compound is formed as a result of mixing two salt solutions.

Taber and Coll (2002) suggest that the conventional sequence in which different types of bonding are introduced, where covalent bonding is taught before ionic bonding, might cause students to believe that all chemical structures are based on molecules. Therefore, the authors suggest teaching metallic bonding first, followed by ionic bonding, and covalent bonding last. Moreover, when covalent bonding is introduced,
they suggest starting with giant covalent lattices before discussing discrete covalent molecules. However, if the bottom-up framework is used, different bond types are presented as points on a continuum rather than entirely distinct concepts. This allows students to experience variation, which is important because variation theory suggests that some critical aspects can only be distinguished by learners if they have previously experienced variation in those aspects (Pang & Ling, 2012). Marton (2009) similarly claims that learners cannot discern without experiencing difference, and cannot experience difference without simultaneously seeing at least two relevant examples of the phenomenon or aspect in question.

I agree with the claim of Levy Nahum et al. (2008) regarding the advantages of the bottom-up framework. However, because its reliance on abstract theoretical ideas may cause difficulties for some students, I believe that the framework suggested by Taber and Coll (2002) could also be used at the upper secondary level without hindering students’ ability to subsequently grasp the more advanced models used at higher educational levels. However, if the framework of Taber and Coll is used at the upper secondary level, the teacher should incorporate the quantum mechanics-based description of electrons in atoms as “probability clouds” of negative charge around the nucleus to establish the idea that ionic and covalent bonding are extremes on a continuum rather than wholly different phenomena. In addition, the different types of bonding should be presented at the same time to allow the students to experience variation and to assist them in discerning critical aspects.

**Improvement of teachers’ professional knowledge and changing teaching practice**

As discussed in the background section, the concept of pedagogical content knowledge (PCK) has successfully been used to describe the unique and distinctive knowledge base characteristic of science teachers (e.g., Abell, 2007; Kind, 2009; Shulman, 2015). Like all professionals, teachers have a constant need for growth, exploration, learning, and development (Villegas-Reimers, 2003). Their PCK must
therefore be continuously developed, and the professional development of a teachers can be seen as an ongoing learning experience that begins during teacher training and continues until retirement (Luft & Hewson, 2014). This is a complex process in which teachers should be seen as knowledge producers rather than knowledge receivers (Park & Oliver, 2008, p. 278). In their model of teacher learning, Luft and Hewson (2014) see teaching as ontologically related to learning (Luft & Hewson, 2014). Therefore, teachers must participate in professional development activities in which they can conduct their learning as knowledge producers in order to improve their teaching practice and student learning (Luft & Hewson, 2014).

Teaching experience is important for the development of PCK (Friedrichsen et al., 2009; Loughran et al., 2006). All but one of the teachers participating in the first study had taught Chemistry in an upper secondary school for at least five years. These teachers were aware that many students found chemical bonding challenging, and provided several examples of their students’ alternative conceptions and difficulties, most of which had been described extensively in the literature. However, few of the teachers explicitly stated that they had chosen to use a specific representation to improve their students’ understanding. This indicates that the teachers did not considered students’ difficulties when deciding how to teach chemical bonding. Moreover, the teachers were generally unaware of how the representations they used could contribute to difficulties in understanding among students, and they did not reflect extensively on their teaching practices. Most of the instructional strategies practiced by the teachers were neither subject- nor topic-specific. In addition, the strategies they used to evaluate students’ understanding were not actually capable of determining whether all of the students had understood the topic. Consequently, there was considerable scope to improve the teachers’ knowledge of their students’ understanding, and their repository of instructional strategies could be expanded to incorporate strategies that better address students’ understanding of chemical bonding. The results of this study also showed that despite their experience, the teachers had generally not made especially strong connections between their knowledge of students’ understanding, representations, and instructional strategies. This shows that
experience without reflection is not necessarily enough to drive the development of teachers’ PCK. Recent studies have emphasized reflection on teaching experiences and students’ difficulties as a key factor in PCK development (Drechsler & Van Driel, 2008; Nilsson, 2009; Tuan et al., 1995). Because it appears that both experience and reflection are essential for the development of PCK, I wanted to explore ways of systematically reflecting on teaching practice to improve teachers’ professional learning and develop their PCK.

The results presented in paper IV show that an intervention based on the learning study approach using the CoRe improved the participating teachers’ PCK development and caused several changes in their teaching practice. These changes revealed that the components of PCK were connected, and prompted the development of several PCK components at once. Paper II showed that in the absence of interventions, teachers are likely to unreflectingly use representations of chemical bonding (i.e. they are unlikely to take students’ understanding into consideration when selecting representations of chemical bonding for use in teaching). Paper IV shows that reflection on students’ understanding emerged naturally from the more general reflections conducted during the group discussions. The teachers discussed and reflected on students’ understanding in relation to the representations of chemical bonding used in their lessons, prompting changes in the representations that the teachers chose to use. That is to say, their knowledge of their students’ understanding became linked to their knowledge of representations. These changes were often initiated by the researcher sharing research results. That is, research results were integrated during the learning study, as described by Vikström (2014). The exercise had particularly pronounced effects on the teachers’ ways of representing metallic bonding. The results of this study also show how such reflections can help teachers to develop their content knowledge: several of the participants mentioned their own lack of knowledge about metallic bonding.

Knowledge of students’ understanding was also connected to knowledge of instructional strategies. For example, the teachers considered their students’ understanding when they changed the framing of laboratory work. The teachers also made connections
between knowledge of students’ understanding, representations and instructional strategies. For example, they suggested showing students representations of molecules in which atoms of a given element are shown in different colours in different molecules to prevent students from coming to believe that the colours used to represent individual elements corresponded to the colours of those elements at the macroscopic level.

The results presented in paper II show that it can be difficult for teachers to identify effective instructional strategies for evaluating students’ understanding. However, the results presented in paper IV show that over the course of a learning study using the CoRe, the participating teachers developed new evaluation strategies: whereas they initially relied on verbal summaries, by the third iteration of the process they had started asking their students to create concept maps to show their understanding of the topic. They found this beneficial because it gave the students an opportunity to create their own pictures of their understanding. Knowledge of the students’ understanding was thus integrated with the teachers’ knowledge of instructional strategies.

The results in paper II also show that the teachers were often unable to specify their students’ difficulties or were slow to do so, although some were able to provide examples after some reflection. This is consistent with what is highlighted by Vikström (2014), who noted that even when teachers are well aware of students’ difficulties in understanding a specific topic, they might be unable to express those difficulties in detail. The results presented in paper IV show that after multiple cycles of lessons combined with a CoRe exercise, the teachers had become much more able to specify their students’ difficulties. Moreover, their answers to the prompt in the CoRe relating to “difficulties and limitations connected with teaching” became more sophisticated and more comprehensive, focusing on critical aspects that must be discerned to understand the object of learning rather than individual items that students find difficult to understand. This indicates that the teachers had adopted the framework of variation theory to at least some extent, and illustrates how their knowledge of their students’ understanding developed over the course of the exercise.
Combining learning studies with content representations (CoRe)

Even though the learning study framework is grounded in variation theory while CoRe is a tool used to develop and portray PCK (which is not grounded in this learning theory), I used both these interventions to explore how they can be combined to improve the development of teachers’ PCK. There were multiple reasons for adopting this approach. First, learning studies have several characteristics that are recognized as being important for PCK development: new knowledge is built on prior knowledge from different domains and experiences of practice, the process includes interactions with students and colleagues (Clarke & Hollingsworth, 2002) as well as reflections on teachers’ own practice (Drechsler & Van Driel, 2008; Nilsson, 2009; Tuan, Jeng, Whang, & Kaou, 1995); there is a strong focus on students’ outcomes, experiences in practice, and learning from the act of teaching (Gess-Newsome, 2015; Henze & Van Driel, 2015; Park & Oliver, 2008); and stimulated recall interviews are used to identify and address discrepancies between teachers’ intentions when teaching and their actual behaviour in the classroom, i.e. their enacted teaching (Gess-Newsome, 2015; Henze & Van Driel, 2015). The learning study framework provides an opportunity to explore both the intended teaching (expressed PCK) and the actual teaching and behaviour in the classroom, i.e. the enacted teaching, as well as the relationship between them. Moreover, the learning study approach has recently been used to improve science teachers’ PCK (Nilsson, 2014; Vikström, 2014), and was proven to be a useful tool for integrating research results into teachers’ teaching practice (Vikström, 2014). Moreover, a combination of a lesson study (Fernandez & Yoshida, 2004) and CoRe was recently proven to improve pre-service teachers’ potential to start developing their PCK (Juhler, 2016). In addition, many studies have shown that the task of developing a CoRe challenges teachers’ thinking. Teachers often struggle to individually construct the Big Ideas of a particular topic and to answer the prompts of the CoRe (Cooper et al., 2015). Therefore, it can be helpful to work collaboratively and to use a facilitator to stimulate and focus the group discussion (Cooper et al., 2015), which is done in a learning study. Two separate CoRe exercises (CoRe1 and CoRe2) were conducted, the first before the cycles of lessons in the
learning study and the second after. Comparing the results of these two exercises clearly showed that the learning study cycles had improved the teachers’ ability to perform a CoRe, i.e. they made the CoRe more comprehensive. For example, the teachers became more able to justify their choices of specific representations or activities. The importance of being able to justify such choices was stressed by Wickman (2014). In CoRe2, the teachers also exhibited more developed Big Ideas, were better able to provide examples of the difficulties and limitations connected with teaching, and provided stronger justifications to explain why it was important for students to understand specific points. In addition, as noted above, their reflections on the students’ understanding during the second CoRe were clearly influenced by variation theory. Finally, the use of CoRe appeared to enhance the effect of the learning study: the experience of formulating Big Ideas and focusing on reflections about what, why and how to teach facilitated the planning of the lesson and reflections on the videotaped lessons. This was particularly beneficial in the studied case because the teachers had not studied variation theory to the extent that is suggested in some publications. Therefore, variation theory was not fully adopted during all phases of the study, which could be seen as a weakness. Nevertheless, the results obtained show that the use of CoRe during a learning study makes it possible to use this framework without requiring the participating teachers to conduct time-consuming studies of variation theory. This is likely to be important in the design of professional development programmes.

Implications for teaching and the design of professional development programmes

Chemistry education and science education in general would greatly benefit from bridging the gap between research and teaching practice, and from determining who should be responsible for constructing the necessary bridge and how it should be constructed. This thesis shows how professional development based on interventions such as learning studies and CoRe can incorporate research findings into teaching practice, and how teachers’ PCK can be developed to improve students’ understanding. The incorporation of research results into teaching
practice is very important: after all, the purpose of science education research is surely to help improve teaching practice and students’ outcomes.

This thesis contributes towards this purpose by expanding the knowledge base relating to the teaching and learning of chemical bonding, and by providing new knowledge about important aspects of teaching of models in general and how the representations of models used in textbooks and by teachers might cause students difficulties in understanding.

To design effective professional development programmes for teachers, one must understand how teachers’ PCK develops (Hence & Van Driel, 2015). This thesis shows how collegial and systematic reflection during a learning study combined with CoRe can enhance the formation of connections between PCK components and thus develop both the individual components and the overall structure of teachers’ PCK. These findings are relevant to research on PCK, training of in-service as well as pre-service teachers and teacher education. Moreover, several studies have shown improving teachers’ professional learning through learning studies enhances students’ learning (Pang & Ling, 2012). Developing teachers’ PCK can thus be expected to benefit the students’ learning. In addition, this thesis reinforces the importance of treating teachers as active learners in professional development programmes. If such programmes are organized using a bottom-up approach, which entails work with and by teachers, and where teachers are not expected only to gain more knowledge, their professional learning is more likely to be improved (Loughran et al., 2006; Nilsson, 2014). This thesis also shows the effectiveness of classroom-embedded and topic-specific professional learning.

The factors that the teachers in this study became aware of in their teaching are relevant to contexts other than that of teaching chemical bonding, and will not only benefit the teachers who participated in the study. For example, the results obtained show that teachers must have a clear idea of how the students are intended to understand the object of learning, why it should be understood, and which critical aspects should be discerned. They also underline the importance of the
strategies, patterns of variation, tasks, and organisation of content used to make this understanding possible.

This thesis also reinforces the point that reflection on teaching experiences and students’ difficulties are crucial for developing PCK. The teachers’ statements in both studies indicated that they rarely reflected on their own practice, possibly because of a lack of time, a lacking tradition of reflection in their schools, the way their schools were organized, or simply a failure to recognize the importance of reflecting. From my own experience as a chemistry teacher, I am fully aware of teachers’ difficult working conditions, which were mentioned by some of the participating teachers, and I wish to emphasize that none of the discussion in this thesis is intended to be interpreted as judgement or blaming of the teachers in any way. It is important that school leaders and the authorities responsible for schools (in Sweden, commune-level politicians) support teachers’ professional development and ensure that they have access to high quality professional development programmes. To achieve this and bridge the gap between research and practice, there is a need for cooperation between university academics (e.g. researchers in science education), teacher educators, school leaders, and the responsible authorities of schools. Teachers must also be involved in this cooperation because their participation is required for the realization of research-based changes in teaching practice to improve students’ learning (Justi & Gilbert, 2002b).

Further research

The new frameworks for chemical bonding discussed in this thesis should be further investigated to determine whether their use helps to prevent the occurrence of common alternative conceptions and difficulties, and to what extent they can improve students’ understanding. As noted above, while there is an extensive empirical knowledge bases of students’ alternative conceptions of and difficulties in understanding chemical bonding, such knowledge bases do not exist for most academic topics (Smith & Banilower, 2015) even though knowledge of students’ understanding is recognized to be a vital
component of teachers’ PCK (Park & Chen, 2012; Smith & Banilower, 2015). Therefore, there is arguably a need for further research on students’ understanding of other scientific topics. It is equally important for the findings of such studies to be communicated to teachers and incorporated into their teaching practice, which has not yet been done effectively for research findings relating to the teaching of chemical bonding. Hence, there is also a strong need for more studies on ways to incorporate the results of science education research into teaching practice.

There is also a need to evaluate the long-term persistence of the effects of the professional development programme examined in this thesis, i.e. to determine whether the changes in teaching practices discussed in paper IV will remain stable over an extended period of time and whether the teachers will apply the knowledge they acquired in other contexts or when teaching other topics. More research is also needed to determine whether such interventions can be applied on larger scales involving other teachers and contexts; the study presented in this thesis involved only a few teachers and only addressed the teaching of one topic (chemical bonding). Participation in learning studies is time-consuming, so it would be interesting to determine whether it is possible to design professional developments that involves collegial and systematic reflections on teaching practice in other ways. Conducting a CoRe can also be demanding and time consuming, and cannot be done for every topic. Therefore, research is needed to determine how a teacher’s professional learning can be improved using the results of a CoRe in which they did not participate directly. It will also be important to determine how important the researcher’s influence as a facilitator is in determining the success of a CoRe.
References


Teaching and learning of chemical bonding models

Many complex real-world phenomena can only be understood using models that make the abstract visible and provide explanations, predictions, descriptions, or simplifications. However, research has shown that students have difficulties understanding models used in science education in general, and particularly chemical bonding models.

This thesis examines various aspects of the teaching and learning of chemical bonding, and its presentation in textbooks and by teachers. It is shown that the representations used by teachers and in textbooks can cause students to have difficulties in understanding, which teachers were generally unaware of. Teachers rarely justify their choices specifically to overcome students’ difficulties, suggesting that their knowledge of how to teach chemical bonding could be improved.

A learning study in which teachers collaboratively explored and reflected on their own teaching practice significantly improved their presentation of chemical bonding, their awareness of students’ understanding, and their ability to justify their choices.

Overall, this work shows that there is a gap between research and teaching practice, and that effective ways of incorporating research results into teaching practice are needed to improve teaching and learning in chemistry.