Faculty of Technology and Science
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Models in chemistry education

A study of teaching and learning acids and bases in Swedish upper secondary schools

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"Skriver du en bok, pappa?
Kan du det? ...
Du skojar".

(Matilda, februari 2007)

Abstract

This thesis reports an investigation of how acid-base models are taught and understood in Swedish upper secondary school. The definition of the concepts of acids and bases has evolved from a phenomenological level to an abstract (particle) level. Several models of acids and bases are introduced in Swedish secondary school. Among them an ancient model, the Arrhenius model and the Brønsted model. The aim of this study was to determine how teachers handle these models in their teaching. Further, to investigate Swedish upper secondary students' ideas about the role of chemistry models, in general, and more specific, of models of acids and bases.

The study consisted of two parts. First, a study was performed to get an overview of how acids and bases are taught and understood in Swedish upper secondary schools. It consisted of three steps: (i) the most widely used chemistry textbooks for upper secondary school in Sweden were analysed, (ii) six chemistry teachers were interviewed, and, (iii) finally also seven upper secondary school students were interviewed. The results from this study were used in the second part which consisted of two steps: (i) nine chemistry teachers were interviewed regarding their pedagogical content knowledge (PCK) of teaching acids and bases, and (ii) a questionnaire was administered among chemistry teachers of 441 upper secondary schools in Sweden.

The results from the interviews show that only a few teachers chose to emphasise the different models of acids and bases. Most of the teachers thought it was sufficient to distinguish clearly between the phenomenological level and the particle level. In the analysis of the questionnaire three subgroups of teachers were identified. Swedish upper secondary chemistry teachers, on the whole, had a strong belief in the Brønsted model of acids and bases. However, in subgroup one (47 %) teachers' knowledge of how the Brønsted model differs from older models was limited and diverse. Teachers in subgroup two (38 %) and three (15 %) seemed to understand the differences between the Brønsted model and older models, but teachers in subgroup 2 did not explain the history of the development of acids and bases in their teaching. Instead they (as teachers in subgroup one) relied more on the content in the textbooks than teachers in the third subgroup. Implications for textbook writers, teaching, and further research are discussed.

List of papers

Paper I

Textbooks' and teachers' understanding of acid-base models used in chemistry teaching. Drechsler, M. and Schmidt, H.-J. *Chemistry Education: Research and Practice, 6* (1), (2005) 19-35.

Paper II

Upper secondary school students' understanding of models used in chemistry to define acids and bases. Drechsler, M. and Schmidt, H.-J. *Science Education International. 16* (1), (2005) 39-53.

Paper III

Experienced teachers' pedagogical content knowledge of teaching acid-base chemistry. Drechsler, M. and van Driel, J. H. *Submitted to Research in Science Education*.

Paper IV

Teachers' knowledge and beliefs about the teaching of acids and bases in Swedish upper secondary schools. Drechsler, M. and van Driel, J. H. *Submitted to International Journal of Science Education*.

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1 Introduction

1.1 Models in science education

Teaching and learning science concerns an understanding of the issues (e.g., concepts) that shapes science. For teachers it is important to know students' conceptions and learning difficulties of these concepts. According to cognitive theories of learning, students construct their own mental concepts when trying to understand scientific concepts (Pines and West, 1986). Depending on the students' background, experience, attitude, and ability, their conceptions will differ from the scientific ones (Nakhleh, 1992).

Scientific concepts have a label (name) and a content (meaning) (Schmidt and Volke, 2003). For instance, a concept may contain a category of similar phenomena sharing certain attributes, e.g. the concept labelled "oxidation" may have the content "all oxidation reactions". A concept may also contain a theory or an explanation of a phenomenon, e.g. the concept "oxidation" may contain the explanation "electron transfer between particles". As a third example, a concept may also be a strategy for solving problems (Eybe and Schmidt, 2004).

One important aspect of the development of scientific knowledge is designing and using models. Models link theories with a target – a system, an object, a phenomenon or a process. They are parts of theories scientists develop to describe, explain and predict aspects of the world-as-experienced *"A model is a readily perceptible entity by means of which the abstractions of a theory may be brought to bear on some aspects of the world-as-experienced in an attempt to understand it"* (Gilbert et al. 2000, p. 34). Models can be distinguished into categories, for instance, scientific consensus models, historical models, and curricular models. A scientific consensus model is a working model used by researchers at a given time. A historical model is an old and often simpler model, which was a consensus model of its time. Curricular models are simplified versions of historical models or scientific consensus models used in school curricula. There are also pedagogical or teaching models. These models are teacher crafted explanations, often in the form of metaphors or analogies. A model in chemistry may be a mental instrument, such as abstract ideas of chemical processes, or more tangible, such as ball and stick models. Further, processes and properties of a target can be represented by mathematical models such as equations and diagrams (Harrison and Treagust, 2000).

There is no model that can describe all properties of a target. If it was able to, it would not be considered a model since each model only emphasises a specific part of the target (Harrison and Treagust, 1998). A model should have most of the following characteristics (Van Driel and Verloop, 1999):

- A model is related to a target; the target of interest is represented by the model.
- A model is a research tool, used to obtain information about a target that cannot be observed or measured directly.
- A model is characterised by certain analogies to the target. This enables researchers to derive hypotheses about the target from the model. These hypotheses may then be tested against the target.
- A model is kept as simple as possible by deliberately excluding some aspects of the target
- A model may be developed through an interactive process in which empirical data from the target may lead to a revision of the model.

When new ideas are added to an existing scientific concept, the content of the concept is revised while the label remains. In this way a concept may have several meanings, for instance, the concept "oxidation" may consist of different models, such as the gain of oxygen atoms, the loss of electrons, or the increase in oxidation number (Schmidt, 1997). Schmidt (1997), and Schmidt and Volke (2003), suggested that some of the students' problems with understanding chemistry originate from the shift of meaning of a concept, that is, a new model is introduced, all using the same label (Figure 1).

In teaching, scientific concepts are usually introduced to students with simple, often older, models. Later, students are given more sophisticated, often newer models. Justi and Gilbert (2002) reported that students may be confused when a new model is introduced, and may combine attributes from different models. It is therefore important to discuss the difference between the models and clearly explain why the new model is introduced. Boulter and Gilbert (2000) considered it important for students to learn about models and their uses, while recognising their limitations in science. This would allow students to gain a better understanding of both the facts and how scientific knowledge is achieved. The students may realise that a phenomenon can be explained in different ways, that is, that several models can be used for the same target. Nuffield Chemistry claims: *"Pupils must learn to see the interplay between* *observed fact and explanation ... and to appreciate how science develops through this interplay"* (Nuffield Foundation, 1968, p. 5). Science education research should, therefore, provide teachers with information that can be used to overcome students' problems in this process. In this thesis, the teaching and learning of different models used to explain acid-base reactions will be studied.

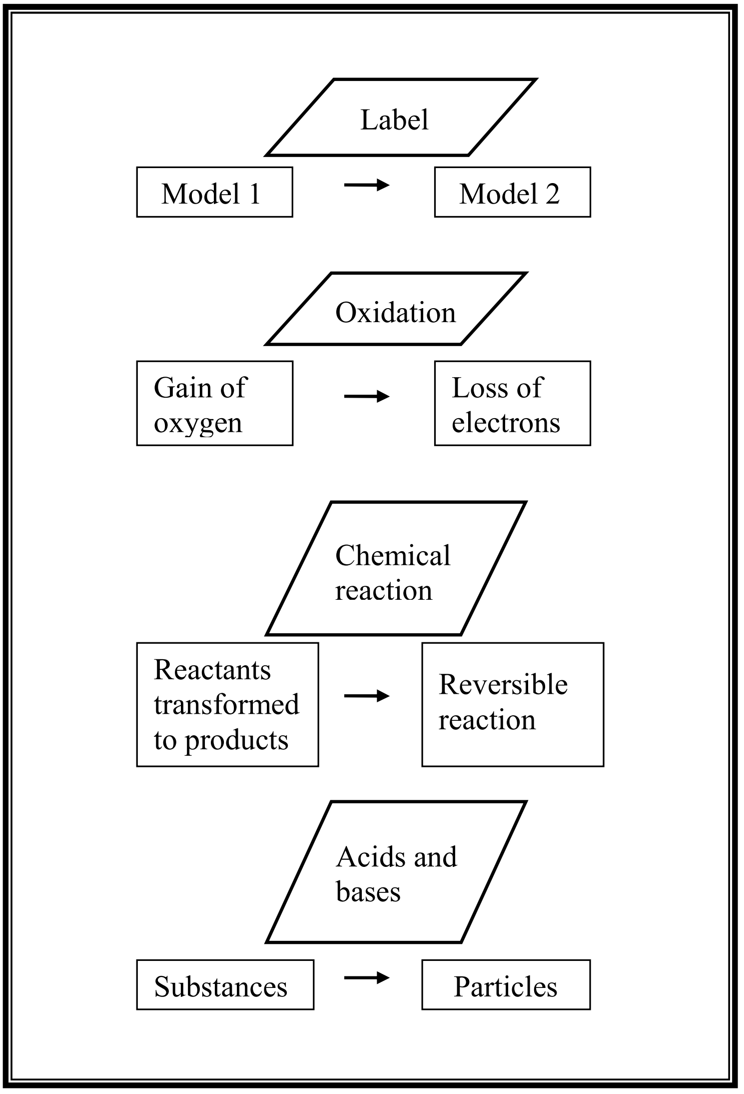

Figure 1. Shift of meaning of concepts in chemistry

1.2 Models explaining acids and bases

The concepts of acids and bases are amongst the basic principles in school chemistry curricula. Acids and bases are also recognised from everyday life in the contexts of food digestion, acid rain, food preservatives, soft drinks, corrosion, and drugs. Further, in popular culture, acids are recognised from horror movies and comic books where acids often are used to destroy metal objects, or eat away human flesh. The concepts of acids and bases have evolved from phenomenological to abstract definitions. At the phenomenological level, they can be defined in terms of their properties, for instance, aqueous solutions of acids turn blue litmus red, neutralise bases, etc. At the abstract level, or particle level, the acidic properties are explained as interactions between particles. Bases can be defined accordingly. The Swedish curriculum emphasises the role of models in chemistry (cf. The Swedish National Agency for Education, 2006b). Therefore, teaching acids and bases is a good opportunity to discuss the use of different models to explain certain phenomena. The history of the scientific development of acids and bases has been described and explained as follows (cf. Hägg, 1989 p. 301-308; Oversby, 2000):

1.2.1 An ancient model

The alchemists defined acids on the basis of their sour taste. In 1663, Boyle explained acids as substances with sour taste and the ability to give red colour to plant dyes like litmus. Acids were also known to react with non-precious metals and carbonates. The opposites of acids were alkalis, recognised by their soapy feeling and their ability to neutralise acids. They were also able to give blue colour to litmus. Reactions between acids and bases resulted in salts which lacked the characteristics of the reactants. This ancient model is still in use and as a model it has some predictive power, for instance, according to this model, phenol is an acid, that reacts with the base sodium hydroxide to form a salt. Among the limitations of this model we find that

- acids must be solved in water for valid descriptions,
- it does not explain the characteristics of a certain acid,
- it does not indicate the limitation of its predicting power (phenol does not react with sodium carbonate).

1.2.2 Lavoisier model

In 1770, Lavoisier tried to explain combustion and its products. Coal, phosphorus and sulphur burning in oxygen were seen to produce acidic oxides. Lavoisier, therefore, concluded that acids were substances containing oxygen. In Lavoisier's acid-base model acids are explained as non-metal oxides and bases are explained as metal oxides. A salt would be formed by the reaction between an acidic oxide (acid) and a basic oxide (metal oxide).

1.2.3 Priestley model

In 1810, Davy demonstrated that hydrogen chloride showed acidic properties even though it did not contain oxygen. About the same time, Priestley suggested that acids were substances containing hydrogen and this theory took over after Lavoisier's. The use of chemical formulas at this time made it possible to make some stoichiometric predictions using this model. One limitation was that the focus was still on the substances included. Also the bases were still thought of as acid neutralisers and no general structure was suggested. The use of this model today is mostly limited to the context of organic chemistry where acidic properties in molecules are explained by two different types of hydrogen: acidic hydrogen and "normal" hydrogen.

1.2.4 Arrhenius model

In 1887, Arrhenius introduced the theory of electrolytic dissociation, for which he was awarded the Nobel Prize in 1903 (Arrhenius, 1903). He connected the acidic properties to the hydrogen (H^+) ion; the higher the concentration of H^+ ions, the more acidic the solution. Acids were defined as substances that could produce H^+ ions in a water solution. Bases were defined analogously as substances that in water solution would produce hydroxide (OH^-) ions. In a neutralisation reaction between an acid and a base, hydrogen ions from the acid react with hydroxide ions from the base forming water. Arrhenius wrote the equation as follows (Arrhenius, 1903):

(1) "$(H^+ + Cl^-) + (Na^+ + OH^-) \rightarrow (Na^+ + Cl^-) + HOH$"

The equation can be simplified as follows:

(2) $H^+ + OH^- \rightarrow HOH$

The Arrhenius model refers on one side to substances (phenomenological level), equation (1), and on the other side to particles (particle level), equation (2).

This model describes strong and weak acids in terms of their dissociation constant. The model also explains the change in conductivity when acids are diluted. The pH-scale was also introduced. The limitations are that acids and bases are still considered as substances and the model is limited to water as a solvent.

1.2.5 Lowry-Brønsted model

In 1923, Brønsted (and at about the same time, Lowry) suggested a more general acid-base definition. According to Brønsted, acids and bases are particles, that is, molecules or ions. Acids are defined as particles that donate protons while bases are defined as particles that accept protons. When an acid donates a proton it becomes a base. An acid and a base that are connected in this way are said to be a conjugated acid-base pair. If, for example, the acid HA donates a proton, the base A^- remains. If the base B^- accepts a proton, the acid HB is formed. A proton transfer according to Brønsted can be written in general terms like this:

(3) $\text{Acid}_1 + \text{Base}_2 \rightleftarrows \text{Base}_1 + \text{Acid}_2$

or as an ionic equation

(4) $HA + B^- \rightleftarrows A^- + HB$

Reaction equation (3) and (4) show that in a Brønsted proton transfer reaction acids and bases are always present.

Since a substance must contain a proton to be qualified as a Brønsted acid all Arrhenius acids are also Brønsted acids. This does not hold for Arrhenius bases accordingly. Ammonia, for example, does not contain hydroxide and, therefore, cannot be labelled an Arrhenius base. Equation (5) illustrates, however, that NH_3 molecules accept protons.

(5) $NH_3 + H_2O \rightleftarrows NH_4^+ + OH^-$

NH_3 is, therefore, a Brønsted base. Equation (5) illustrates that the formation of water or salt is not necessarily a prerequisite for a Brønsted acid-base reaction.

Further, the Brønsted model is not limited to water as a solvent. Neutralisation in water is written as:

(6) $H_3O^+ + OH^- \rightleftarrows 2H_2O$

Neutralisation in liquid ammonia would be:

(7) $NH_4^+ + NH_2^- \rightleftarrows 2NH_3$

1.2.6 Lewis model

Brønsted's proton transfer can be seen as a special case of the more general Lewis definition where acids are defined as electron pair acceptors and bases as electron pair donators. The focus is set more on bindings than on particle transfer which gives the acid-base concept a new dimension since this model now explains more reactions. The limitation is, however, that the acid-base concept looses its significance since almost all reactions can be seen as acid-base reactions. Today this model is mostly used in organic chemistry (describing, explaining, and predicting the basic properties of amines).

1.2.7 Further models

In 1939, Usanovitch suggested a general solvent model for acids and bases. Anions were considered carriers of an electron pair. Acids were any particle that increased the cation concentration in the auto-protolysis of a solvent. For instance, in the auto-protolysis of liquid ammonia, equation (7), an acid would increase the ammonium ion (NH_4^+) concentration.

In 1954, Gutman and Lindqvist suggested that in a general acid-base definition, the transfer of ions should be emphasised. An acid is defined as a cation donator, or an anion acceptor. A base is defined as a cation acceptor/anion donator. The Brønsted model can here be seen as a special case, cation transfer for protons. Neither of these suggested models are in much use.

1.3 Acids and bases in the Swedish school curriculum

1.3.1 Swedish National curriculum for science and chemistry

The National Swedish curriculum for upper-secondary school was revised in the year 2000. In the curriculum for the science program in upper secondary school (age 16-19), the use of models is emphasised as a crucial ingredient in education (The Swedish National Agency for Education, 2006a). It states (translated from Swedish):

> *"The development of knowledge builds on interaction between experienced based knowledge and theoretical models. Model thinking is fundamental for all disciplines of natural science, as well as, for other scientific fields. In education, a development of understanding that our comprehension of natural phenomena consists of models, often described by using mathematical language, should exist. These models change and refine as new knowledge emerge. A historical perspective contributes to illustrate the progress the science disciplines have gone through and their importance to society"*.

Further the curriculum announces that schools have the responsibility that the students after graduation have the ability to: *"apply a scientific working method for problem solving, model thinking, experimentation, and theory construction"*. Finally, the importance of models is also listed in the curriculum for chemistry (The Swedish National Agency for Education, 2006b). It says (translated from Swedish) that the goal for education should be for the student to: *"develop their ability to use scientific theories and models to interpret and explain chemical processes'*. Further, *'develop their ability, from chemical theories, models and own experiences, to reflect upon observations in their surroundings"*. Regarding acids and bases for the introduction chemistry course (The Swedish National Agency for Education, 2006c), the Swedish curriculum states (translated from Swedish):

> *"After the course, the students should have knowledge of the pH concept, neutralisation, strong and weak acids, as well as, be able to discuss chemical equilibrium, for instance, in the context of buffer solutions and relate this knowledge to, among other things, environmental issues".*

One of the main changes in the revision of the curriculum for the introductory chemistry course was the relocation of the chapter about chemical equilibrium to the advanced course. In effect, this move influenced changes in the teaching of acids and bases. The section on weak acids and bases, as well as the section on buffer solutions, has been shortened. There is less focus on calculations and more emphasis on understanding the acid-base concept. To fit the new curriculum, the Swedish chemistry textbooks were revised in the year 2000.

1.3.2 Acid-base models in the curriculum for the upper secondary school

When acids and bases are introduced in school, several models are used. In Sweden, the acid-base concept is introduced in lower secondary school (ages 14-16) and the concept is further developed in upper secondary school (ages 17-19). Chemistry can be taught both on a phenomenological level, dealing with substances, and on a particle level. In the lower secondary school, the students are not supposed to have a full understanding of the particle theory and, hence, chemistry is taught mainly on the phenomenological level. In a chemical reaction all reactants and products are considered as substances and reaction equations are written with a formula equation model. Formula equations identify the *substances* that are involved. Hence, an acid-base reaction is written as follows:

(8) Acid + Base → Salt + Water

When used in acid-base reactions, the formula equation model is a simplified version (curricular model) of the historical Arrhenius' acid-base model. In upper secondary school, chemistry is taught mainly on the particle level and an ionic equation model is introduced. Ionic equations name the *particles* that are involved in a reaction. Acid-base reactions are described by ionic equations as proton transfer reactions according to Brønsted's acid-base model. Two major applications of acid-base reactions are discussed, neutralisation and buffer solutions.

Neutralisation

Equations (2) and (8) suggest that in a neutralisation reaction, acids and bases consume each other. The result is a neutral solution. This is, however, not always true. If equivalent amounts of a weak acid, for instance, acetic acid (HOAc) react with a strong base, e.g., sodium hydroxide (NaOH), the resulting solution will be basic. This phenomenon can be attributed to a reaction between acetate ions and water molecules (9).

$$(9)\quad AcO^- + H_2O \rightleftarrows OH^- + HOAc$$

Buffer solution

A buffer solution is one that resists a change in pH to a certain extent when either acids or bases are added. Since formula equations suggest that acids and bases consume each other, buffer solutions are more easily explained with the Brønsted acid-base model in which acids and bases co-operate and exist together. A buffer solution consists of a weak acid (HA) and its conjugate base (A^-). Since the weak acid represents the best source of protons when OH^- ions are added to the solution, the following net reaction takes place:

$$(10)\quad OH^- + HA \rightleftarrows A^- + H_2O$$

The net result is that OH^- ions are not allowed to accumulate but are replaced by A^- ions. Similar reasoning is valid when acids are added to the buffer solution. Because A^- has a high affinity for protons, oxonium ions do not accumulate but react with A^- to form HA. The conjugated acid-base pairs in equilibrium will, in this way, hold the $[OH^-]$ and $[H_3O^+]$ relatively constant and, therefore, stabilise the pH value within a certain pH interval.

Lewis model and later models are not introduced in the Swedish upper secondary school. Instead, in Sweden, the teaching of acids and bases has a strong focus on the phenomenological level (which might be explained by the ancient model and the Arrhenius model) and on the sub-microscopic level (explained by Brønsted model). Therefore, these models are more central in this study!

1.3.3 Earlier research in teaching and learning acids and bases

Earlier research shows that textbooks are not clear about how they explain the use of different models for acids and bases. Carr's (1984) study of chemistry textbooks showed that the books did not clearly distinguish between the Arrhenius model and the Brønsted model. No explanation was provided why a new model was introduced and how a new model differs from the earlier one. In a survey, Oversby (2000) identified chemistry textbooks that explained different acid-base models but did not discuss the strengths and limitations of each model. Further, in the application sections, the books did not refer to any specific model and the models were treated as facts. De Vos and Pilot (2001) studied the past and the present of the chemistry curriculum in the Netherlands. Several layers (or contexts) of knowledge were identified that had been added to the curriculum in the course of the historical development. The authors showed that in many modern textbooks these layers are not well connected and sometimes inconsistent with each other. As a result chemistry teachers and students are confronted with incoherent acid-base models that are difficult to teach and to learn. Furió-Más, et al. (2005) and Gericke and Drechsler (2006) showed that textbooks introduce new models in a non-problematic way, and have a linear, cumulative view of models of acids and bases, as if there were no conceptual gaps between the different models. This suggests that scientific knowledge grows linearly and is independent of context, and no progression between the models can be seen. Instead, the way models are used in textbooks suggests that different models of a phenomenon constitute a coherent whole; that is, different models are seen as different levels of generalisation. In this way, attributes from a simpler or older model would be valid in all later models as well. According to Justi (2000), this idea could lead to learning problems among students.

Research also points out that teachers' knowledge regarding models and use of models vary. For instance, Van Driel and Verloop (1999, 2002) said that the teachers' views on models are narrow and incongruous. Further, they showed that teachers' use of models is not related to the number of years of teaching experience, nor to the school subject they teach. Justi and Gilbert (1999, 2000) reported that teachers use hybrid models instead of specific historical models in their teaching. Hybrid models result from a transfer of attributes from one model to another. They also showed that many chemistry textbooks do not discuss why scientists use different models. Bradley and Mosimege (1998) studied pre-service teachers' conceptions about acids and bases. They concluded that the pre-service teachers had difficulties understanding the Arrhenius model.

Several studies show that students have difficulties in understanding the acid-base concept. Nakhleh (1994) reported that upper secondary students were unable to fully understand the acid–base chemistry because they had weak understanding of the particular nature of matter. Cros, et al. (1986) found that university students know how atoms and molecules are constructed. The students, however, tended to use descriptive definitions of acids and bases, such as $pH < 7$ or $pH > 7$. Further, they had problems identifying bases. Ross and Munby (1991) found that upper secondary students had difficulties writing and balancing ionic equations and difficulties in describing bases on the particle level. There are additional studies that go more in depth discussing the problems students encounter when the course changes from the Arrhenius model to the Brønsted model. Rayner-Canham (1994) showed that many students enter college courses with a strong belief in the simpler Arrhenius model of acids and bases. Therefore, students must be clearly informed about the benefits of introducing a more complex model. Hawkes (1992) noticed that student-thinking is still dominated by the Arrhenius model, in which only OH^- ion-producing substances are considered as bases. He suggested that the Brønsted model should be introduced first and that the Arrhenius model should only be used as a historical footnote. Schmidt (1991) showed that students have problems in understanding the concept of neutralisation. It was also reported that students may have difficulties in understanding conjugated acid-base pairs (Schmidt, 1995). Together, the latter two studies also indicate that students may not fully understand the Brønsted acid-base model. Schmidt and Volke (2003) found that upper secondary school students have problems to distinguish between redox reactions with acids and acid-base reactions. Further, they found that students have difficulties in accepting water as a base. Demerouti, Kousathana, and Tsaparlis (2004) reported that students from upper secondary school believed it would require a larger amount of NaOH to neutralise a strong acid than an equivalent amount of a weak acid. Further, they showed that students are more familiar with the Arrhenius model; and that they do not use the Brønsted model to explain the properties of acids and bases.

Students' understanding of the use of models in general has also been studied. Gilbert (1991) illustrated that the students considered models as artificial representations of reality, however, they did not see scientific knowledge as artificial. Gilbert concluded that if science is defined as a model building process, it could promote both students' scientific literacy and their understanding of the artificiality of knowledge as a human construction. Grosslight et al. (1991) found that eleventh grade honour students saw models as representations of real-world objects or events rather than as representations of ideas about real-world objects or events. The students thought that the purpose of using different models for the same target was to capture different spatiotemporal views of the target and not different theoretical views. Further, models were seen as means to communicate information and not as means to test and develop ideas or theories.

1.4 Teachers' practical knowledge

An individual teacher's behaviour is highly determined by individual experience, personal history (including learning processes), personality variables, subject matter knowledge, and so on. This personal knowledge base serves as a filter when a teacher interprets new information. However, not all knowledge a teacher has plays an important role in his/her actions. Teachers might withhold a viewpoint and focus on certain aspects during teaching. The term "teachers' practical knowledge" is often used to indicate the knowledge and insights that underlie teachers' actions in practice (Verloop, Van Driel and Meijer, 2001). Teachers practical knowledge is conceptualised as action oriented and person bound (Van Driel, Beijaard and Verloop, 2001). Teachers' practical knowledge has been labelled in different ways by different authors. Each label indicates which aspect of knowledge the authors find most important. The most commonly used labels are: personal knowledge, professional craft knowledge, action oriented knowledge, situated knowledge, tacit knowledge, and knowledge based on reflection and experiences (Verloop, Van Driel and Meijer, 2001). A special form of practical knowledge which refers to teaching subject matter is pedagogical content knowledge (Van Driel, Verloop and de Vos, 1998).

1.4.1 Pedagogical content knowledge (PCK)

In upper secondary education, teachers' knowledge is strongly related to the subject taught (Meijer, Verloop and Beijaard, 1999). When addressing teachers' knowledge in teaching a specific topic, teachers' pedagogical content knowledge

(PCK) is usually addressed. PCK has been introduced to fill the gap between content knowledge and pedagogical knowledge. PCK differs from content knowledge because of the focus on the communication between teacher and student. PCK also differs from general pedagogical knowledge because of the direct relationship with subject matter (Verloop, Van Driel and Meijer, 2001). PCK was first introduced by Shulman (1986) as a form of teachers' special practical knowledge the teachers need to help students understand specific content. According to Shulman the key elements of PCK are: (a) knowledge of representations of subject matter, and (b) understanding of specific learning difficulties. In a later article, Shulman (1987) included PCK into "the knowledge base for teaching". This knowledge base consisted of three content related categories (content knowledge, PCK, and curriculum knowledge) and four categories related to general pedagogical knowledge (learners, their characteristics, educational contexts, and educational purposes). In terms of the features integrated, the concept of PCK has been further elaborated by several scholars. Grossman (1990) identified three main domains – subject matter knowledge, pedagogical knowledge, and context knowledge – that influence teachers' PCK. Magnusson, Krajcik and Borko (1999) proposed that the concept of PCK could be described as a "mixture" or "synthesis" of five different types of knowledge: orientation toward science teaching, knowledge of science curriculum, knowledge of science assessment, knowledge of students' understanding, and knowledge of instructional strategies. Carlsen (1999) suggests that the dynamic nature of PCK should be emphasised and that PCK should not be seen as a static body of knowledge. Van Driel, Verloop and de Vos (1998) said that two key elements of PCK are essential in all research about teachers' knowledge. These elements are: (a) teachers' knowledge about specific conceptions and learning difficulties with respect to a particular content, and (b) teachers' knowledge about representations and teaching strategies. These are the same as Shulman's key elements of PCK. According to De Jong, Van Driel, and Verloop (2005), these two components are intertwined and should be used in a flexible manner. The more a teacher knows about students' difficulties, with respect to a certain topic, and the more strategies they have to their disposal, the more effective they can teach this topic.

To promote teachers development of their PCK over time, the most important aspects reported are disciplinary education (Sanders, Borko, and Lockard, 1993) and classroom teaching experience (Van Driel, De Jong, and Verloop, 2002).

The impact of classroom teaching experience is enhanced by reflections on their own teaching (Osborne, 1998).

1.4.2 Teachers' beliefs

The ways teachers teach a specific subject are also, more or less, related to teachers' beliefs. Teachers' knowledge and teachers' beliefs are related. Beliefs act as organizers of teachers' knowledge (Tobin, Tippins, and Gallard, 1994). For instance, if a teacher is using constructivist ideas, he or she would organise and teach his/her knowledge in another way than a teacher with other beliefs. Several studies have, however, reported discrepancies between teachers' beliefs and practice. Mathijssen (2006) suggested three different aspects that might explain these differences: (a) the nature of the belief, the more abstract a belief is, the more likely there will be discrepancy with practice, (b) research methodology, qualitative studies involving a small number of teachers limit the possibility to model a relationship between beliefs and practice, and (c) educational context and personal characteristics, including general factors and resources such as time available which may place serious constraints on the way teachers translate their beliefs into practice. Although teacher beliefs and knowledge are highly personal, there will be elements which are shared by groups of teachers, for instance, teachers who teach the same subject to pupils of a certain age level (Verloop, Van Driel, and Meijer 2001).

Teachers are influenced by the material selected, especially textbooks which constitute the main source of classroom material used. However, school chemistry textbooks are not very clear about the role of models in general (cf. Gericke and Drechsler, 2006; Justi, 2000) nor about models regarding acids and bases (cf. Carr, 1984; de Vos and Pilot, 2001; Furió-Más, et al. 2005; Oversby, 2000). As a result, chemistry teachers and students are confronted with incoherent acid-base models which are difficult to teach and to learn. A strong belief in the authority of the school textbooks might result in less communication of different ideas about concepts in the classroom (Van Boxtel, Van der Linden, and Kanselaar, 2000). Instead, the textbook is seen as a kind of dictionary where all facts are collected.

Research has reported that teachers' beliefs, once formed, are very hard to change. When new curriculum materials are imposed upon teachers, they may implicitly, intuitively or even explicitly, resist implementing such materials. A new curriculum would be more easily accepted by teachers when it is in accordance with their own beliefs regarding learning goals, or when it is a possible solution to problems they recently have experienced (Johnston, 1992). García-Barros et al. (2001) found that primary school teachers are especially influenced by an educational tradition, characterised by an emphasis on memorising and reproducing facts and concepts. Kagan and Tippins (1993) studied pre-service teachers' beliefs about students during their teaching practice. They found that secondary teachers' beliefs change very little over time compared with elementary teachers. They concluded that secondary teachers' beliefs were more associated with academic achievement. Changes of the professional self are difficult and time consuming because of a stable system of knowledge and routines, developed over many years (Lang, 2001). Science teachers often move through 15-20 years of schooling without being stimulated to reflect on their own beliefs about the nature of science (Gallagher 1991). Further, Gallagher reported that secondary teachers pay little attention to the nature of science and instead teach science as an objective body of knowledge.

Finally, there are other aspects besides teachers' knowledge and beliefs that might influence how a topic is taught. For instance, the teacher might feel insecure in his/her teaching role. Treagust and Gräber (2001) said that beginning senior high school teachers stress the teaching of facts and concepts more than experienced teachers. Science teachers are also struggling with the tension of teaching science topics in depth, versus having not enough time to cover the entire breadth of the provided curriculum materials (Whigham, Andre, and Yang 2000).

2 The aim of this study

The overall aim for research in chemical education is to gather knowledge and understanding that can be used to improve chemistry teaching and learning. This study focused on the different models used to explain acids and bases in the Swedish upper secondary school. The aim of the present study was to determine how chemistry textbooks and chemistry teachers handle different models used to explain acid-base reactions. Further, this study aimed to contribute to a more profound knowledge about how students reason about acids and bases. Data were collected in several steps or cycles. The results from the first cycle were used for the next cycle of design and investigations. Each cycle is presented in a separate paper. In paper 1, Swedish chemistry textbooks for upper secondary school were analysed and Swedish upper secondary school teachers were interviewed regarding how they teach acids and bases. In paper 2, students were interviewed regarding how they understand acids and bases. In paper 3, teachers' PCK of teaching acids and bases was investigated. In paper 4, teachers' beliefs of teaching acids and bases were investigated.

The specific research questions were:

Paper 1

1. How do Swedish chemistry textbooks for upper secondary school present:
    - the concepts of acids and bases?
    - the use of models in general?
2. How do Swedish upper secondary school teachers
    - teach the concepts of acids and bases?
    - introduce the concepts of models in their teaching?

The results from this cycle were used in the next cycle in order to investigate which difficulties students might have in understanding acids and bases.

Paper 2

3. How do Swedish upper secondary school students understand:
    - the concepts of acids and bases?
    - the use of models in science?

Students' statements from this study (as well as, excerpts from the analysis of textbooks in paper 1) were used in the next cycle in order to capture teachers' PCK of teaching acids and bases.

Paper 3

4. What is the content of experienced chemistry teachers' PCK of:
    - students' difficulties in understanding acids and bases?
    - teaching strategies they consider useful to help students overcome such difficulties; in particular, how do they use models of acids and bases in their teaching?
5. How did their PCK of teaching acids and bases develop over time?

The results from this cycle and from paper 1 were used to develop statements regarding teachers' ideas of teaching acids and bases. These statements, together with statements regarding students' difficulties in understanding acids and bases, were used to develop a questionnaire which was administered among a large sample of Swedish chemistry teachers in the 4^{th} and final cycle.

Paper 4

6. What are the Swedish chemistry teachers' knowledge and beliefs of:
    - students' difficulties regarding acids and bases?
    - teaching acids and bases?
    - models of acids and bases?
    - textbooks regarding acids and bases?
7. Can subgroups of chemistry teachers be identified according to their beliefs and use of models in their teaching?

3 Data collection methods

3.1 Examination Board Questions

In a study preceding the main study, students' answers to multiple choice tests from Examination boards in the United Kingdom and the United States were analysed. The results were used to narrow the focus of the main study and to formulate the research questions for the first cycle Examination boards usually do not publish exam questions and test results. However, several boards in the United Kingdom and the United States provided us, for research purposes, with test items and – in some cases – also with the test statistics, that is, the distribution of students' answers against the options (answer pattern). Examination board tests can be seen as a collection of questions based on practitioners' statements about what students should know. Examination board questions in the form of multiple choice questions show, in addition, which alternatives to a correct answer are especially attractive to students. If a student bases his or her reasoning on an alternative interpretation of a concept, he or she will arrive at a certain incorrect answer. If, therefore, multiple choice items are correctly constructed, the incorrect answers (distractors) may hint at problems students have in understanding chemistry concepts (Schmidt, 1991). Based on these reflections we analysed the results of examination board tests.

The provided multiple choice questions were stored in a computer file. By using a computer program about 500 questions dealing with acids and bases were selected from the item bank. The analysis of these items led to a few multiple choice items which had an answer pattern where one distractor was chosen to a higher extent than the others. Three such questions from upper secondary level in the UK are given as examples. The total number of students (n) was not provided.

Item 1: Students were asked to identify the reaction equation that would describe best the reaction between dilute hydrochloric acid and aqueous sodium hydroxide. The correct answer was $H^+ + OH^- \rightarrow H_2O$. Among the distractors, 34 % of the students preferred the following incorrect answers:

- $Na^+ + Cl^- \rightarrow NaCl$
- $Na^+ + Cl^- + H^+ + OH^- \rightarrow NaCl + H_2O$

Item 2: Students were given the following information

$NH_3 (g) + H_2O (l) \rightleftarrows NH_4^+ (aq) + OH^- (aq)$

A. NH_3 reacts as a proton acceptor

B. H_2O reacts as an acid

C. OH^- reacts as a base

The students were asked to choose among options that described the above statements as true or false. 45 % of the students avoided all answer options where water was described as an acid, that is, described statement B as true.

Item 3: Students were asked to identify how nitric acid acts in reaction with copper. A reaction equation was not given.
Among the possible choices of answers, 30 % of the students chose the option "as an acid".

We interpreted the result of our analysis of the examination board questions as follows:

- Item 1. Some students might prefer reaction equations that name salt or water as a product of an acid-base reaction. These students seemed to prefer the Arrhenius model to explain acid-base reactions.
- Item 2. About half of the students did not accept water as an acid or a base. These students did not consider Brønsted's proton transfer model to explain acid-base reactions.
- Item 3. All students had not realised that, in this case, nitric acid does not act as an acid only, but as an oxidising agent as well.

The result of analysis of the examination board items helped us to focus this study towards the understanding and use of different models of acids and bases in Swedish upper secondary chemistry and to develop the research questions for the first cycle. It was also decided to use the items 1 and 2 given above in the interviews with the chemistry teachers in cycle 1. They were asked to comment on the examination results. The students in cycle 2 were asked to complete the questions and give comments on their choices.

3.2 Textbook analysis (Paper 1)

An analysis of the textbooks most widely used in upper secondary schools in Sweden was performed in order to investigate how they:

- introduce the acid-base concept
- present acid-base reactions
- generally treat models in chemistry
- treat models in the acid-base context.

The textbooks analysed were: Andersson, et al. (2000), Borén, et al. (2000), Henriksson (2000), and Pilström, et al. (2000). To find the information needed, the acid-base chapters of the four books were analysed considering how they introduce and present the following concepts:

- Acid
- Base
- pH
- Acid-base reaction
- Redox reaction
- Neutralisation
- Salt
- Buffer solutions

All equations in the acid-base chapters were analysed and categorised as:

- Formula equation
- Ionic equation
- Hybrid between the two former models
- Redox reaction

The chapters were also searched for an introduction to Brønsted's model. Further, the introductions to all books were read in order to investigate how they present chemistry models in general. For the same reason the contents of the books were searched via their indexes. Finally the acid-base chapters were searched for explicit use of models.

3.3 Semi-structured interview (used in Papers 1, 2, and 3)

The strategy chosen was a semi-structured interview based on Kvale (1996). Semi-structured interviews mean that, on the one hand, the questions used in the interviews were predetermined. On the other hand, the interviews were also open for teachers' and students' unexpected ideas. Therefore, some interview questions were added to the later interviews. The interviews were conducted at the interviewees' schools and were tape-recorded and transcribed for later analysis. The interview guide consisted of four phases; first a *briefing phase*, followed by a *warm-up phase*, the *main phase*, and finally a *debriefing phase* at the end (Figure 2). The briefing and debriefing phases were not tape-recorded. The interview guides are described in the respective paper's appendices. In the *briefing phase* the purpose was to make the interviewees comfortable with the situation. It was important that the interviewees trusted the interviewer, so that they would open and talk freely to a stranger. The briefing phase consisted of a short presentation of the project and the interview procedure was discussed (duration, use of tape-recorder etc.). The interviewees gave their permission to tape-record the interview and use the recording for research purposes and were assured about their right to withdraw from the interview at any time (Brickhouse, 1992 and Kvale, 1996). The interviewees could also ask questions concerning the interview procedure. The purpose of the *warm-up phase* was to approach the topic and induce the interviewee to talk freely. This was done by asking general questions about the chemistry curriculum. Further, descriptive and general information about the interviewees were collected. In the *main phase* the research questions were addressed.

Sometimes, after the interview there could be some tension or anxiety because the interviewee had exposed him/her self and was wondering about the purpose of the interviews. The interviewee could also have felt emptiness, because he or she had given away information and not received anything in return. By turning off the recorder the interviewee might felt relieved and some issues in the interview could be addressed again, more freely. The interviewees had an opportunity to add comments on the content which were not recorded and ask questions of any kind. During the *debriefing phase*, the research project was also described in more detail. The interviewees could also comment on the interview procedure and how they felt during the interview. The interviewees were informed about their right to withdraw the permission to use the tape for research purposes once again (Brickhouse, 1992 and Kvale, 1996).

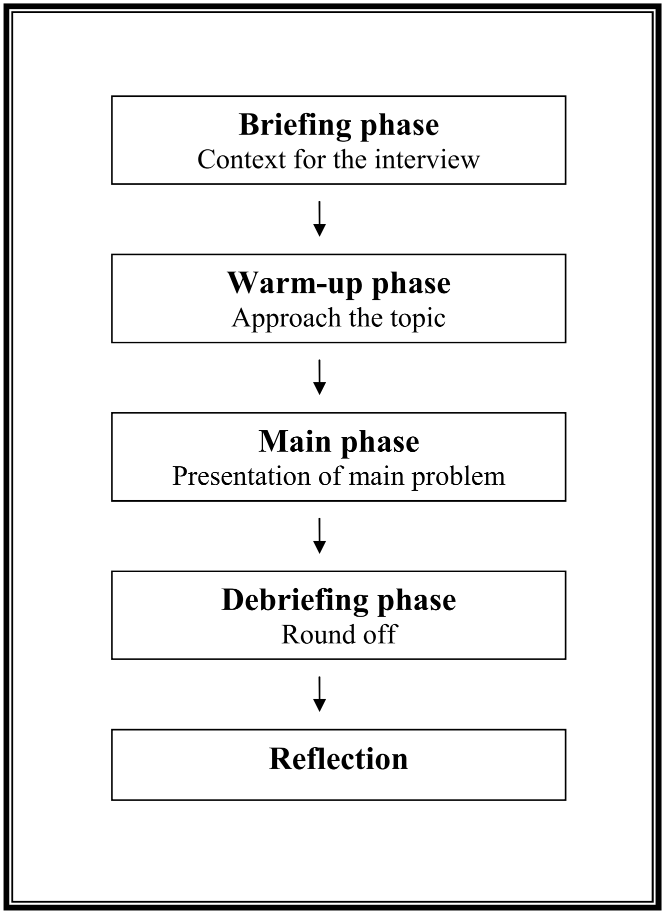

Figure 2. Flowchart of a semi-structured interview

After the interviews were conducted, the interviewer took notes concerning aspects the tape-recorder could not document, such as statements from the interviewees in the debriefing phase, the atmosphere during the interviews and the interviewees' behaviour.

3.4 Story-Line method (used in Paper 3)

In order to capture the complexity and diversity of teachers PCK for specific subjects, several authors have suggested that multi-method design with triangulation should be applied (e.g. Kagan, 1990; Baxter and Lederman, 1999). Meijer, Verloop, and Beijaard (1999) used a structured open interview in combination with a concept mapping assignment in order to investigate language teachers' practical knowledge about teaching reading comprehension. Henze (2006) used semi structured interviews and a questionnaire in order to identify patterns in science teachers' knowledge regarding the introduction of a new syllabus. Further, narrative methods such as the story-line method have been used to capture the development of teachers' knowledge. Therefore, in order to complement the interview data, the story-line method (developed by Gergen, 1988) was implemented in the interviews in the third cycle (Paper 3; see Research Question 5) of the study. The use of this method in research on teachers' practical knowledge has been evaluated by Beijaard, Van Driel, and Verloop (1999) by reviewing the use of the story-line method in studies on experienced teachers' practices and events in their careers. They concluded that the story-line method was helpful in respect of evaluating changes through individual teachers' careers regarding a certain aspect of teaching.

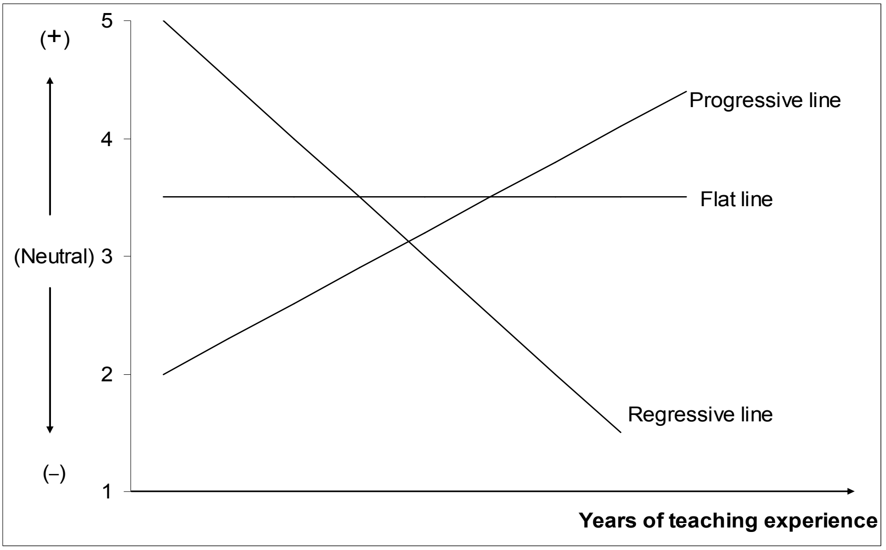

Figure 3. Ideal-typical story-lines

In the present study, teachers were asked to draw story-lines in connection with the main phase of the interviews. In the story-lines, the teachers described how their level of satisfaction with teaching acids and bases had developed over the years. A rudimentary form of a story-line consists of progressive, flat and/or regressive lines (Figure 3), with which many combinations and variations can be constructed. The teachers graded (on a five-point scale where 1 was considered very dissatisfied, 3 neutral, and 5 very satisfied) how satisfied they were with their teaching of acids and bases, at the present. Then the teachers constructed the story-line from the present to the past. By starting from the present, it is easier for the respondent to start thinking about the aspect of teaching in question and draw lines towards the past. A reverse procedure appears to be more difficult for the respondents (Beijaard, Van Driel, and Verloop, 1999). Finally, the teachers were asked to comment on the story-lines, explaining what had caused the direction or the change of direction or incline.

3.5 Questionnaire (used in Paper 4)

Since the other parts of this study only involved small samples of teachers, the aim of the fourth and final cycle of the study was also to improve our understanding of teachers' beliefs of teaching acids and bases by consulting the entire population of Swedish chemistry teachers. Therefore, a questionnaire was constructed and mailed to all Swedish upper secondary schools of which we could find addresses. The questionnaire consisted of two parts: (1) a series of questions focusing on teachers' age, sex, number of colleagues who taught chemistry, years of experience as a chemistry teacher, academic qualification, what textbook they used, form of employment (regular-, temporal employment or substitute teacher), and what other school subjects they taught; (2) a series of items consisting of statements about the teaching of acids and bases. The design of the second part of the questionnaire was inspired by the results that were collected earlier in this study and reported in paper 1. Statements were formulated which focused on the topics found in study 1, such as students' difficulties regarding acids and bases, the use of Brønsted model and other models regarding acids and bases, teachers' use of textbooks, and so on. A set of 31 items was constructed to cover the different ideas that were brought up by the teachers during the interviews. Items had to be scored on a 4-point Likert-type scale where 1 means disagree and 4 means agree (William, 2006). A preliminary questionnaire was presented in a seminar with six other science education researchers to ensure its clarity and comprehensiveness (Isaac and Michael, 1997). In this seminar the formulations and the order of items in the questionnaire were discussed, after which the final version of the questionnaire was made.

For the analysis of part 1, descriptive statistics were performed to characterise the composition of the response group in terms of age, sex, prior education and qualifications. These data were compared with data from the Swedish National Agency for Education to ensure that the respondents could be qualified as a representative sample (National Center for Educational Statistics, 2006). For part 2, frequencies, mean scores, standard deviations, and missing values were computed for all items. In order to reduce the amount of data, five scales were constructed using Principal Component Analysis (PCA). These scales were subjected to an analysis of reliability, focusing on the value of Cronbach's alpha, and the effect on this value when deleting items from the scale, and the item-total correlations. We aimed at obtaining the highest possible value of Cronbach's alpha for these five scales, including as many items as possible (Pedhazur and Pedhazur Schmelkin, 1991; 109-110). Following this, the mean scores and standard deviations of the newly obtained scales were computed. Next, Pearson correlations were calculated to explore relationships between the scales. Analysis of variance (ANOVA) was performed to investigate whether the teachers' scores on the scales differed significantly with respect to the personal characteristics from part 1 of the questionnaire. Finally, a cluster analysis was performed to investigate if subgroups of teachers could be identified. All statistical analyses were performed using SPSS (Statistical Package for the Social Sciences) software, version 14.0.

4 Short descriptions of the studies

4.1 Overview study (Papers 1 and 2)

The studies in cycles 1 and 2 (see chapter 2) were performed to get an overview of how acids and bases are taught and understood in Swedish upper secondary schools. These studies consisted of the following steps: the most widely used chemistry textbooks for the upper secondary school in Sweden were analysed, six chemistry teachers, and finally seven students were interviewed.

4.1.1 Samples

Instead of drawing the teachers at random from a larger population, chemistry teachers who were known (by our research group) to have an interest in reflecting and discussing teaching matters were invited. This strategy has been discussed by Miles and Huberman (1994, p. 268). All teachers had participated in evening lectures at the university where results from research in chemistry education were presented. They were between 35 and 60 years old, had at least eight years of teaching experience and were teaching at four different upper secondary schools. Five of the teachers had Master's degrees. All of them used the same textbook, Andersson, et al. (2000) as textbook in their upper secondary chemistry teaching.

At upper secondary level, acid-base chemistry is taught in an introductory course and in an advanced course. For the interviews, students from upper secondary schools were invited. They had completed both courses and ranked at the top of their chemistry classes. This measure was taken in order to find interviewees who might be more willing to discuss chemistry problems in a reflective way (Miles and Huberman, 1994, p. 268). Three teachers, employed at three different schools in central Sweden, were asked to select top students on the basis of their chemistry achievements. Seven students (three girls and four boys) took part in the interviews. All students had used their chemistry textbook regularly and they had completed all the exercises. Two students had also used extra-resource books to improve their understanding especially in areas that were not clearly explained in their "official" textbooks.

4.1.2 Analysis

The interviews lasted about 45 to 60 minutes and were transcribed in full. From the transcripts, summaries of four pages per interview were written. The transcripts were first analysed using a provisional lists of categories that emerged naturally from the research questions and the interview guides (Miles and Huberman, 1994, p. 58). The transcripts of the interviews and the summaries were read by two researchers independently. After discussions, consensus was reached and the final lists of categories were developed.

4.1.3 Main results

Step 1: Analysis of chemistry textbooks
The four textbooks used in this study (see section 3.2) were not clear regarding the use of models in chemistry. One of the books analysed describes the term model in the introduction. In three books, the term model is mentioned in connection with atomic models. Two of these books thoroughly explain how models can be used. In the third book the term model is mentioned in the context of the atom, but not explained. All textbooks present pictures of ball-and-stick molecular models. In this context the term model is named, but not discussed.

In the context of acids and bases, we found that the books use various models without being explicit about this use. There were no discussions of the following:

1. the fact that models are used,
2. why different models are used in parallel,
3. what model is in use at the moment,
4. the scope and limitations of each model.

Step 2: Interviews with teachers
All teachers agreed that it is important for the students to know that chemistry knowledge can be acquired by using models. They admitted that they had not discussed this aspect satisfactorily with the students. They reported, however, difficulties applying their general view of models to specific topics, for instance, acid-base reactions. The only example the teachers gave about the use of models in chemistry was the atomic model.

Further, the teachers did not see Arrhenius and Brønsted acid-base definitions as models used to explain the properties of acids and bases and their reactions. In addition, teachers had difficulties to see the differences between the models. The teachers were aware of differences between the definitions of acids according to Lewis and to Brønsted. However, they did not recognise the older definitions. It may be that the teachers have too much confidence in the school chemistry textbooks and use them as the primary source of information in preparation for their lessons.

Step 3: Interviews with students

Several students stated that the result of an acid-base reaction is a neutral solution. The students were also reluctant to consider water as an acid or as a base. Further, in the case of hydrochloric acid, the students sometimes identified H^+ as the acid and sometimes HCl. A similar contradiction was also found with sodium hydroxide (confusion of OH^- and NaOH). In their explanations the students also confused the concepts acidic and acid, and also basic and base. This might explain why students were reluctant seeing water as an acid or as a base.

When the students discussed the use of models in chemistry they seemed to have a good understanding of models. They explained models as research tools for testing hypotheses. Further they said that models are simplifications of reality and that they provide a way to relate to abstract phenomena.

The students seemed to have difficulties in applying their general knowledge about models to the acid-base concept. In the first phase of the interviews several students mentioned a change of meaning of the acid-base concept which indicates that they, in fact, were aware of the introduction of a new model. However, when asked to write or explain acid-base equations, they used attributes from different models.

The following attributes from the Arrhenius model were found in the interviews:

- acids and bases are substances,
- in an acid-base reaction, acids and bases consume each other,
- an acid-base reaction results in a neutral solution,
- in an acid-base reaction, salt and water are formed,
- substances react forming new substances.

The following attributes from the Brønsted's model were found in the interviews:

- acids and bases are particles,
- proton transfer, an acid donates protons and a base accepts protons,
- mixing of equivalent amounts of an acid and a base will not always result in a neutral solution,
- in an acid-base reaction an acid reacts with a base forming a new acid and a new base,
- the formation of a salt is not a prerequisite for an acid-base reaction,
- spectator ions should be deleted in the reaction formula.

When the students were confronted with having used different models in different tasks they tried to explain that the equation (8)

(8) $\text{Acid} + \text{Base} \rightarrow \text{Salt} + \text{Water}$

is the same as the equation (3).

(3) $\text{Acid}_1 + \text{Base}_2 \rightleftarrows \text{Base}_1 + \text{Acid}_2$

Since water can act both as an acid and as a base, the student assumed that salt could also be either an acid or a base and, therefore, they saw the two models as one and the same.

4.2 Experienced teachers' pedagogical content knowledge of teaching acid-base chemistry (Paper 3)

4.2.1 Sample

The aim of this study was to examine the use of Brønsted and older acid-base models in teaching practice. Therefore, we needed a sample of teachers that were aware of these various models. Upper secondary chemistry teachers that had participated in a teacher training course arranged by our university two years earlier were interviewed. In that course, students' difficulties, as well as, the use of models in acid-base chemistry, electrochemistry, and redox reactions had been discussed. The aim of the course was not to provide the teachers with new teaching strategies, but to make them aware (a) that students' difficulties in understanding sometimes resulted from inconsistencies in their teaching, and (b) of the role of models in science and science education. Nine of the teachers volunteered to be interviewed about two years after the course. These teachers were from different parts of Sweden and they were not involved in the first part of this study. The descriptions of the teachers are summarised in Table 1. No interventions took place during the two years, but each school year the teachers had at least one opportunity (perhaps more, depending on their school) to try out new ways of teaching acids and bases, using ideas they got from the course.

Table 1 Description of the teachers interviewed in this study.

Teacher	Gender	Age	Years of experience	Type of school	Number of colleagues	Teaching a second subject
T1	Male	35 - 40	10	small	0	Mathematics
T2	Male	~50	20-25	medium	3	Mathematics
T3	Female	> 60	>25 (15 in upper secondary school)	medium	3	Mathematics
T4	Male	> 60	>25	medium	3	Biology
T5	Male	~50	20-25	large	8	Mathematics
T6	Male	35 - 40	10	medium	3	Mathematics
T7	Female	~50	20-25	medium	2	Biology
T8	Male	> 60	>25	medium	3	Biology
T9	Female	35 - 40	10	medium	2	Mathematics

4.2.2 Analysis

The interviews were analysed according to the following seven steps.

1. The interviews were transcribed in full.
2. The transcripts were read repeatedly to get an overview of the interviews.
3. In order to facilitate the discussion between the two researchers who analysed the transcripts, summaries per question and per teacher were written in English.
4. From these summaries main categories and subcategories were identified by the two researchers separately. The categories and subcategories were then discussed until consensus was reached.
5. The categories were applied to the full interview transcripts by the author. If a category was mentioned several times by a teacher, in response to different questions or in different contexts, the category was marked for every time it was mentioned. In this way, the teachers were given scores on the different categories. In order not to overlook important categories and to validate the list of categories, a third researcher was called in for this step. The third researcher was asked to apply the categories to one of the interviews and also to check the pattern of scores for each category. The results from this interrater check showed minor differences, and after discussion consensus was reached.
6. When the final list of scores was developed, relations and patterns for every teacher were looked for, again by both authors. Further, the categories were compared to the teachers' statements from the story-lines.
7. Finally, all categories and scores for each teacher were listed in a table (see Table 2 below). In this way, patterns of categories amongst the teachers could be compared and analysed. Similarities and differences between the teachers' PCK about acids and bases were identified.

The analysis of the story-lines was done in the same way. The categories from the teachers' comments on the different parts of their story-lines were listed separately and compared with the list of categories from the rest of the interviews in step 6 above.

4.2.3 Main results

Teachers PCK of students' difficulties in understanding acid-base chemistry

The teachers' explanations of the students' difficulties in understanding acids and bases were classified in the following four categories: (a) students' misinterpretations of acid/base reaction equations, (b) students' preconceptions, (c) model confusion, and (d) students' difficulties in distinguishing between explanations at the phenomenological (macroscopic) level and at the particle (sub-microscopic) level. The distribution of the categories among the teachers is presented in Table 2.

Regarding category a (misinterpretations of the equation), a variety of examples were discussed, such as "Students do not realise that the products they suggest will react further", or "Students make up alternative paths for the reaction". Further, students were also said to use the wrong charge for ions, or to forget to check the balance of the charges. Finally, students were said to prefer water and salt amongst the products in an acid-base reaction.

Regarding category b (preconceptions), the most often mentioned preconceptions were the following: (i) acids and bases are hazardous or poisonous, (ii) only strong acids were taken into account, (iii) only substances containing a hydroxide ion were considered bases, and (iv) acids and bases were defined as substances. Finally, all teachers but one said that students treated weak acids as if they were strong.

Regarding category c (model confusion), only five of the interviewed teachers said that they discussed the different models of acids and bases explicitly with their students. These five teachers thought that most of their students would recognise the limitations and scope of each model. The other four teachers were not aware of this problem in their own teaching because the different models were used at different times or in different contexts.

Regarding category d (level confusion), five of the teachers said that students confused what they saw at a phenomenological level with explanations on a particle level. Students were said to have a preference for using substances instead of particles in their explanations. They often confused acidic solution with acid, and basic solution with base. The teachers said it was important to be clear about which level was being discussed at a particular moment, and why.

Table 2. Teachers' distribution of categories and scores. The more marks (x) a teacher has in a category, the more the teacher addressed the category in different questions or in different excerpts.

Students' difficulties	T1	T2	T3	T4	T5	T6	T7	T8	T9
General									
Calculations	x	x					x	x	x
Writing and interpreting equations	x			x	x				
Bases	x					x			
Comments on excerpts									
a. Misinterpreting the equation	x	xxxx	xxx	x	x		x		
b. Pre-conceptions	x	xx	xx	x	x	x	xx	xx	xx
c. Model confusion	xx	x	x	xx	x	x	xx	x	xx
d. Level confusion		xx	xx	xx	xxx	xxx	xx	xx	x
Models									
Students accept that different models coexist	x	x		x	x	x			x
Teachers' use of models of acids and bases	xxx		x	x	x	x	x	x	xxx
Three models are introduced	x								x
Two models are introduced			x	x			x		
Emphasis on sub-micro- and macro- levels		x			x	x		x	
Reasons for changing the method of teaching acids and bases.									
a. Reflection on students' difficulties	xxx	xx	xx	xx	x	x	xxx	x	xx
b. Collegial discussions	x				x	x	xx	x	xxx
c. Research in chemistry education	xx			x	x		x		x
d. Reflection on teaching		x	x		x	xx	xx	xx	
e. New textbook			xx			xxx	xx	xx	x
f. Stimulation		x			xx	x		x	
g. The media		x				xx		xx	
h. Simpler experiments		x		xx	x			x	
What is changed									
Experiments	xx	xx	xx	x	x	x		x	x
Explanations	x		x		x		x	x	x
Calculations			x		x	x		x	
More explicit explanation of models	xx			x	x				x
- " - of sub-micro- and macro- levels		x	x		x	x	x	x	x

Teachers' PCK of teaching strategies and acid-base models in their teaching practice

Six of the interviewed teachers thought that students accepted the use of models in chemistry. To explain this, one teacher said, *"Students accept that since the target is beyond reach, it is represented by a simplification instead."* The teachers also thought that students accepted that different models could be used to explain the same target. Two teachers defined three different models (ancient, Arrhenius, and Brønsted) in their teaching. Three teachers defined two models in their teaching: an "old model" and Brønsted's model. In their "old model", the teachers combined attributes from the ancient model and Arrhenius' model. All of the above teachers thought that students understood the differences between Brønsted's model and the older model(s). The teachers explained a new model as providing a deeper (more complex) explanation. Three teachers also said that it was important to explain that some attributes from the older model could not be used in the new one.

The remaining four teachers did not explain the use of models of acids and bases. They were all aware of the different acid-base models from the course, and most of them used different models in explaining other areas of chemistry, for instance, atoms, bonding, and redox reactions. One reason for not using models to explain acids and bases was that they thought it was sufficient to differentiate between the phenomenological level and the particle level. These teachers defined acids and bases as particles according to Brønsted, but at the phenomenological level the emphasis was not on the acids and bases themselves but on the acidic or basic solutions. These teachers considered it difficult enough for the students to differentiate between these two levels, and believed that introducing more models would make the topic even more difficult for students to understand.

Teachers' development of PCK of teaching acids and bases

In this section, the categories presented emerge both from the interviews and from the story-lines.

Regarding how and what the teachers changed in their teaching methods from year to year, three main activities were mentioned: 1) how a topic was explained, 2) new examples for calculation, and 3) new laboratory work. Four of the teachers said that they had changed their teaching towards a more explicit explanation of models since they participated in the course, while the others said they tried to be more clear about the transfers between the sub-microscopic level and the macroscopic level. Several teachers mentioned explicitly that the time allotted to teaching acids and bases and the content taught were well established and were not changed.

The teachers' reasons for changing how they taught acids and bases were classified into eight categories, referring to (a) reflection on students' difficulties, (b) collegial discussions, (c) research in chemistry education, (d) reflection on own teaching, (e) new textbook, (f) stimulation, (g) the media, and (h) simpler experiments. The distribution of the categories among the teachers is presented in Table 2.

All teachers mentioned reflection on students' difficulties (category a) as a reason for changing how they taught a topic; however, three teachers were vague in their descriptions of how this was done. The other teachers mentioned three ways of identifying students' difficulties: (i) testing students to determine which questions they did not understand, (ii) listening to students' questions and statements during lessons, and (iii) having students evaluate the lessons.

Discussions with colleagues (category b) were said to be an important reason for changing their teaching. Students' difficulties and new experiments aiming at challenging students' "misconceptions" were said to be discussed.

Within the category research in chemistry education (category c) three main aspects were mentioned. Two of the teachers had occasionally participated in courses or workshops at universities near their schools. They both said that this had mainly influenced their teaching at the beginning of their careers. They gained new insights into students' difficulties, and also increased their knowledge of the history and philosophy of science. In recent years, however, they attended university less often: they lacked time, and also felt they did not need the courses to the same extent. One teacher mentioned that he read journals that included articles on research in science education. However, he found it difficult to implement what he learned in this way in his own teaching. Finally, two teachers said they occasionally searched the universities' web sites and in this way found new experimental work.

Regarding reflections on own teaching (category d) two main issues were identified. Two of the teachers focused on students' understanding when changing a teaching strategy. They analysed what they did and how they did it, and if it was understandable and clear. For the other four teachers the focus was directed on the teachers' own actions; for instance, they compared the lesson plan with what they actually did in the classroom, or considered whether the results of an experiment had become as expected. They were also more keen on being scientifically "right".

New textbooks (category e) could result in changes in the way the teachers taught acids and bases. The changes mentioned were new experiments and new examples for calculations.

Changes could be introduced because a new way of teaching was more fun and more stimulating (category f). It was mentioned that doing the same experiments year after year could be boring and it was more stimulating to vary them.

Media (category g) provided a great source of context that was familiar to the students and, therefore, made the topic of acids and bases more interesting for them. Three specific cases were mentioned: an article about acidification in the local newspaper, an advertisement on television for anti-corrosives, and an advertisement, also shown on television, in which mention was made of pH in body lotions.

Regarding simpler ways of teaching (category h), experimental work was said to be changed if the teachers found a new experiment that was cheaper and less time consuming to perform and prepare.

4.3 Teachers' knowledge and beliefs about the teaching of acids and bases in Swedish upper secondary schools (Paper 4)

4.3.1 Sample

Since I was not able to collect addresses of individual chemistry teachers, the questionnaire was mailed to a sample of 441 Swedish upper secondary schools which were available. I estimate that I, in this way, reached about 90% of the Swedish upper secondary schools. The letters were addressed to the "head chemistry teacher", together with an opening letter. In this letter the person that opened the envelop was asked to distribute the six enclosed questionnaires among his or her colleagues. He or she was also asked to make more copies or ask us to send more copies if there were more than six chemistry teachers at the same school. In Sweden, however, chemistry as a separate subject is only taught in the science program. Since all schools do not offer the science programme, the sample of school also contained schools which did not teach chemistry. If this was the case, the letter also requested to return the coded return-envelope empty.

The questionnaire was mailed in March 2006 with a letter of invitation, in which the relevance of the study was explained. After four weeks, a reminder was sent out to the schools that had not yet replied (Cohen and Manion, 1994, p. 83-105).

The useful response consisted of 281 answers of the questionnaires. Since we could not obtain reliable data about the total number of chemistry teachers in Sweden, we calculated the response rate based on the number of schools that replied. Of the 441 schools that received the questionnaire, 225 schools replied. This suggests a response rate of 51%. Sixty-seven respondents, however, replied that chemistry was not taught at their schools. This left us with responses from chemistry teachers from 158 schools. The problem with the above calculation is that it is unclear whether the response rate for schools without chemistry was the same as for schools with chemistry. If, for instance, the response rate for schools without chemistry was higher, because it is easier to reply without having to respond to the questionnaires, the maximum response rate would be 158 / (441-67) = 42%. In any case, the response rate is at least 42 % and probably higher (up to 51%). Note, however, that it was not possible to calculate the response in terms of percentage of teachers.

To check if the questionnaire was distributed well and what teachers thought of it, 25 teachers were randomly selected at a teacher conference in November 2006 at Karlstad University. Two of these teachers had not received the questionnaire because they worked in lower secondary schools. Of the other 23, eight teachers had not responded. The reason they gave for not responding was that they did not have time to fill it in at once, and after some time had passed they thought it would be too late to send it in. The remaining 15 teachers, who had completed the questionnaire, said they thought the statements were relevant to their teaching practice, but three of them said that some of the statements were difficult to answer. Further, these three teachers said that, when reading the statements, they realised that their knowledge of acids and bases could be improved.

4.3.2 Analysis

Construction of scales, PCA

Using principal components analyses with varimax rotation, the original data were reduced to five scales. The five scales referred to:

1. Teachers' knowledge of students' difficulties regarding acids and bases (SD). A high value on the SD scale indicates that teachers believe that students have many different difficulties in understanding acids and bases,
2. Teachers' beliefs about the Brønsted model (BM). A high value on the BM scale indicates that teachers prefer to use the Brønsted model and think that the Brønsted model is clear for students,
3. Teachers' content knowledge of acids and bases (CK). A high value on the CK scale indicates that teachers have a good understanding of the difference between Brønsted and older models,
4. Teachers' use of other models of acids and bases in their teaching (OM). A high value on the OM scale indicates that teachers use a lot of different models in their teaching,
5. Teachers' use of textbooks (UT). A high value on the UT scale indicates that teachers do follow the textbooks strictly in their teaching of acids and bases.

To explore possible relationships between the scales, Pearson correlations were calculated.

ANOVA

To investigate if the variance in the scores on the five scales could be explained by teachers' variables such as age, gender, number of colleagues, years of experience, academic qualification, what textbook they used, form of employment, and what other school subjects they taught, analysis of Variance (ANOVA) was performed.

Cluster analysis

In order to find different answer patterns on the five scales amongst chemistry teachers, and to investigate whether subgroups of teachers regarding their beliefs of teaching acids and bases could be found, a hierarchical cluster analysis was performed. Ward's method, which is designed to optimise the minimum variance within clusters (Hair et al., 1998), was used as clustering method. On inspection of the dendogram, focusing on the large increase of the squared

Euclidean distance between certain steps of the agglomeration process, a three-cluster solution was chosen (Milligan and Cooper, 1985).

4.3.3 Main results

PCA

In Table 3, the number of items per scale, mean values, standard deviations, and finally the internal consistencies (Cronbach's alphas) of these scales are shown. The OM scale got the lowest value (1.6) which indicates that teachers, on the whole, do not explain: 1) different models of acids and bases, and 2) how the concept of acids and bases has evolved during history. The BM scale scored highest (2.97) of the scales which suggests that teachers have a strong belief in the Brønsted model and thought it was quite clearly presented in the textbooks. The CK scale has a mean value of 2.0, which is below the average of 2.5. This indicates that they have a limited knowledge about the differences between Brønsted and older models and do not differentiate between these models of acids and bases. For the SD scale, the value is slightly higher, but it is still below 2.5. This indicates that the teachers score the student difficulties that we suggested in the questionnaire rather low, and, hence, thought that acids and bases were – on the whole – maybe rather easy to understand for students. Finally, the UT scale reached just above 2.5, which suggests that the teachers, on average, are neutral about the use of examples and formulations from their textbook.

Table 3. Descriptive statistics for the developed scales

	N	Number of items	Mean	Std. Deviation	Cronbach's alpha
SD	275	8	2.36	0.47	0.747
BM	272	5	2.97	0.41	0.606
CK	261	4	2.03	0.65	0.558
OM	275	2	1.62	0.69	0.476
UT	280	3	2.53	0.59	0.476
Valid N	252				

Pearson correlations

From Table 4, it can be seen that the BM scale correlates significantly with UT and also, but negatively, with CK and OM. These results suggest that teachers with a strong belief in the Brønsted model (BM) also think that the presentation of the concept of acids and bases is quite clear in the textbooks (UT). They do not differentiate between Brønsted and Arrhenius model (CK), and they do not explain different models, and how these have replaced each other through history (OM). In addition, the OM scale has a significant negative correlation with the UT scale. This suggests that teachers that do use different models of acids and bases in their teaching tend to be less satisfied with the content in the textbooks than others. The CK and OM scales, as well as, the CK and UT scales do not correlate significantly, which indicates that a high content knowledge regarding acids and bases does not necessarily result in teaching different models of acids and bases. Finally, the SD scale does not correlate with any of the other scales. This suggests that teachers' knowledge about acids and bases and their use of teaching strategies is not correlated with their ideas about students' difficulties.

Table 4. Pearson correlations between the scales

	SD	BM	CK	OM	UT
SD	1				
BM	-0.028	1			
CK	-0.034	-0.266(**)	1		
OM	-0.060	-0.225(**)	0.094	1	
UT	0.033	0.309(**)	0.015	-0.231(**)	1

** Correlation is significant at the 0.01 level (2-tailed)

ANOVA

The results of the ANOVA analysis are summarised as follows:

1. Some teachers used English textbooks (e.g. Stanitski et al. 2003). These teachers had significant higher beliefs in the Brønsteds model (BM) and they also used other models in their teaching (OM). The English textbooks were clearer in differentiating between the Arrhenius and the Brønsted model, which the five Swedish books did not. Further, these teachers did not follow the textbook in their teaching very strictly (UT).
2. Female teachers had significant lower beliefs in the Brønsteds model (BM) then men had and did not follow the textbooks as strictly as men did (UT).
3. Teachers between 40 and 50 years of age had a significant higher score on the CK scale. Perhaps these teachers had experience of teaching the Arrhenius model explicitly and, hence, had better knowledge about the differences between Arrhenius and Brønsted model of acids and bases.

Cluster analysis

The respondents were distributed among the three clusters as follows: 47 % were classified as cluster 1, 38% were classified as cluster 2, and 15 % were classified as cluster 3. Next, for each cluster mean scores on the five scales were computed. These mean scores are presented in Table 5. All clusters that were formed had similar mean scores on knowledge about student difficulties (2.3 to 2.4; SD). For the other four scales, the three clusters show three different patterns. Cluster 1 has relatively low scores on the scales for teaching models of acids and bases (CK and OM), an average score on textbook use (UT), and high scores on BM. Cluster 3 has the opposite pattern with relatively high scores on the scales for teaching models of acids and bases (CK and OM) and relatively low scores on UT and BM. Cluster 2 has relatively high scores on CK and UT but a relatively low score on OM. It was concluded that teachers who had a relatively good knowledge of different models of acids and bases, and use these models in their teaching (high scores on OM and CK), believed less strongly in the Brønsted model and did not follow the textbooks to the same extent as did teachers with less knowledge of the different models. In cluster 2 the teachers had relatively high scores on the content knowledge of acids and bases (CK), but they had relatively low score on the scales for different models (OM) and, hence, they seemed to be more satisfied with the content of the textbooks. A series of T-tests showed all differences – except for the SD scale – to be statistically significant.

Table 5. Mean scores of the clusters on the five scales. Relatively high scores are marked in bold and relatively low scores are underlined (at least 0.3 above or below the overall mean for the respective scale)

Cluster	n	SD	BM	CK	OM	UT
1	118	2.4	3.1	<u>1.6</u>	<u>1.3</u>	2.5
2	96	2.3	2.9	**2.4**	1.4	**2.8**
3	38	2.3	<u>2.7</u>	**2.3**	**2.8**	<u>2.0</u>
Mean		2.4	3.0	2.0	1.6	2.5

5 General discussion

The role of textbooks

It seems that for the teachers, the school chemistry textbook was an important source of content knowledge. In paper 1, it was concluded that teachers follow the content and structure from the textbooks quite strictly. The acid-base concept and the model concept were presented the same way by the books and by the teachers. Both teachers and textbooks introduced acids and bases as substances. Later, the Brønsted model was used, but both textbooks and teachers also implicitly used earlier models simultaneously. The textbooks and the teachers however claimed that they used the Brønsted model from the beginning. Most textbooks and all teachers mentioned the formation of salt when talking about the neutralisation reaction. It might be reasonable to introduce acids and bases at the phenomenological level as substances that consume each other. This interpretation of a neutralisation reaction is properly described by formula equations. The Brønsted model, however, defines acids and bases as particles exchanging protons. This is properly interpreted by ionic equations. The analysis of the textbooks and the interviews with teachers revealed that the discussion about the use of models in chemistry was limited to the introduction of the course and to the chapter about the atom. In paper 3, it was found that textbooks play an important part in the beginning of teachers' careers (cf. Treagust and Gräber, 2001). After some years of teaching, the teachers had identified sections that were not clear and began to be more critical about the content in the textbooks. Most of the teachers said that the textbooks were unclear in their distinction between sub-microscopic and macroscopic level. Five of the teachers explained the use of models in the concept of acids and bases. However, three of them explained only two models while two of the teachers explained three models of acids and bases in their teaching. In this way their teaching differed a lot from how the concept of acids and bases is presented in the textbooks. In paper 4, it was seen that teachers that use several different models of acids and bases in their teaching, do not follow the content of textbooks as strictly as other teachers. A strong belief in the authority of the textbooks might result in less communication of different ideas about concepts in the classroom (Van Boxtel, Van der Linden, and Kanselaar, 2000). Instead the textbook is seen as a kind of dictionary where all facts are collected.

The use of models

Research has shown that teachers may be aware that different models exist but do not always know how to use them in their classes (Justi and Gilbert, 2002). The same was observed in the present study. In paper 1, the teachers were well aware of the importance of models but had difficulties in making use of them in explaining the properties of acids and bases. In paper 3, although all teachers had studied several models of acids and bases in a teacher training course two years earlier, only a few teachers chose to emphasise the different models of acids and bases in their teaching. Most of the teachers thought it was sufficient to distinguish clearly between the phenomenological level and the particle level. In paper 4, the results indicated that Swedish upper secondary chemistry teachers, on the whole, had a strong belief in the Brønsted model of acids and bases. 53 % of the teachers understood the differences between Brønsted and older models but only 28 % of these teachers chose to explain the history of the development of acids and bases in their teaching.

Students' understanding of acids and bases

The students in our study realised that chemists used models to understand and explain observations and to test hypotheses. Further, they said that models are simplifications of reality and that they provide a way to relate to abstract phenomena. This result is rather different from the findings by Grosslight et al. (1991) who conclude that the eleventh grade honour students in their study saw models as means to communicate information and not as means to test and develop ideas or theories. However, the students in this study did not connect their general view of models to acids and bases. They were not aware that several models are available to describe acid-base reactions. Research has reported that upper secondary students have difficulties in using the Brønsted model when asked to explain acid-base properties (e.g., Demerouti, Kousathana, and Tsaparlis, 2004). The same was observed in this study. When writing acid-base reactions, students preferred substances, rather than particles, as reactants or/and products. Students also assumed that a reaction between an acid and a base would always result in a neutral solution. This observation is also in line with earlier research on students' understanding of acids and bases (Schmidt, 1991). Schmidt and Volke (2003) reported that students had difficulties to accept water as a base. The students in this study confused the concepts acid, acidic, and acidic substance, as well as the concepts base, basic, and basic substance. This may explain why they were reluctant to accept water as an acid and as a base. Confronted with a formula and an ionic equation for the same reaction several students assumed that both contained the same information. In this study we also found that textbooks and teachers were not clear about the different models used to explain acids and bases. It was inferred that textbooks influenced teachers in planning their lessons. It is reasonable to assume that textbooks influence students studying acid-base chemistry in the same way. Students could, therefore, not be expected to develop correct scientific understanding about acids and bases. Top students were selected for the interviews. If these students had problems in understanding the Brønsted model, this should apply even more to ordinary students. Of course, ordinary students could have other additional problems as identified in the present study.

We expect that other researchers will identify similar problems in the area of acid-base chemistry, at least in Sweden, but also in other countries. There are four reasons for this:

(1) The research questions developed for this study was based on the results of Examination Board questions from the UK. These can be seen as experts' questions to test students problems and therefore to be relevant. This aspect counts for their validity. However, because the results of the Examination Board tests are in line with the results of the interviews with students and interpreted the same way by the interviewed teachers as we did, their generalizability is also assumed.

(2) Some of the difficulties students had in understanding acids and bases have previously been reported. Schmidt (1997) described students' idea that every acid-base reaction would lead to a neutral solution. Schmidt and Volke (2003) found that students had difficulties to accept water as a Brønsted base. Demerouti, Kousathana, and Tsaparlis (2004) showed that students are more familiar with the Arrhenius model and that they do not use the Brønsted model to explain the properties of acids and bases.

(3) The results from the interviews with teachers (Papers 1 and 3) were confirmed in the questionnaire study (Paper 4). For instance, many teachers had a strong belief in the Brønsted model but were not aware of the differences between the Brønsted model and older models (Papers 1 and 4). Teachers that had good knowledge about different

models of acids and bases did not always emphasise these different models in their teaching (Papers 3 and 4).

(4) Some of the findings regarding teachers' knowledge and beliefs in this study can be explained by the results of more general studies. For instance, teachers that had good knowledge about different models did not include this issue in their teaching. Gallagher (1991) reported that secondary teachers give more attention to concepts and principles of science than to the nature of science. Whigham, Andre, and Yang (2000) pointed out that teachers struggle with the tension of teaching the concepts in depth or to cover the whole curriculum. Research has also reported about teachers' strong belief in textbooks (e.g. García-Barros et al. 2001).

As a final remark, although the textbooks seem unclear of the different models used to describe acid-base reactions it is not intended to imply that the textbook authors are unaware of these models. In discussions with textbook authors, a simple and valid argument was given for the presentation of the acid-base concept: to simplify the concept and thereby facilitate learning. This study, however, shows that although students were expected to have learnt Brønsted's acid-base model, most of them had not developed a clear picture of it.

6 Implications

Chemistry courses should provide students with clear explanations of models for acids and bases. The results of the present study emphasise the need for teachers (and textbook authors) to provide students with clear descriptions of the models that are used to explain the properties of acids and bases. Students need to understand why, at a certain point of the course, the Brønsted model is introduced and how this model differs from the one that had been used before. A clear distinction between formula equations and ionic equations has to be made.

It was found (in Papers 1, 3 and 4) that teachers relied on the content in the textbooks. The teachers had, however, not always noticed that their textbooks did not clearly distinguish between the different acid-base models. Teachers should be more critical when reviewing textbooks. Further, in paper 4 it was found that teachers' knowledge of students' difficulties in understanding acids and bases did not correlate with their teaching strategies or beliefs of teaching acids and bases. One explanation might be that teachers were unfamiliar with the difficulties included in the items of the questionnaire. Since the difficulties were derived from earlier research about students' difficulties in understanding acids and bases, I suggest that teachers should learn more about these issues from, for instance, reading journals in science education, in-service courses and teacher education. Finally, in Paper 4 it is suggested that older teachers are more aware of the differences between Brønsted and older models. It can be that older models were more explicitly taught in older versions of the curriculum or during teacher education. Teachers' strong belief in the Brønsted model also suggests that this is the only model teachers recognise from their own education. Hence, I suggest that there should be more emphasis on older models and the history of the scientific development of acids and bases in teacher education.

In paper 2, a few teachers mentioned research as a source of learning about students' difficulties. Further, most of the teachers in paper 3 said that they had made, or at least tried to make, changes in their teaching of acids and bases after the course about students' difficulties and the use of models. One teacher said that he had learned much about models in the course, but felt that a section about how to implement these ideas in teaching would have been useful. He wished for a new course on this. In addition, when drawing his story-line, he said that his level of satisfaction with his teaching of acids and bases had changed during the interview. This indicates that a teacher training course should be followed up with additional discussions about, for instance, how teachers can implement their new ideas and the difficulties that may arise when doing so, and new ideas should be generated for developing their teaching further. Discussing authentic student statements from other teachers was found to be a pleasant and relaxed way of discussing these issues with teachers. This might also be a fruitful way to enhance pre-service teachers' PCK of both (a) students' understanding and (b) teaching strategies to help students overcome their difficulties. Textbooks also play an important part in teachers' planning of lessons, especially at the beginning of their careers but also later on. Pre-service teachers should learn to critically review textbooks. This might also help them to develop new teaching strategies.

More research is needed for a better understanding of the role of models in teaching and learning chemistry. During the interviews, teachers described how they taught acid-base chemistry. It is not clear from the results, however, what really happened in the classroom. In paper 4, the use of questionnaires with Likert-type items to investigate teachers' knowledge and beliefs has certain disadvantages. Although the reliability of this instrument was considered satisfactory in statistical terms, I am aware that the teachers may have interpreted items in other ways than I intended. Further, the statements in the questionnaire were developed from teachers' ideas of teaching acids and bases collected in the overview study. Other ideas than those investigated might have given another explanation of the findings in this study. Therefore, a follow-up study is necessary to validate and further explore the outcomes of this study. For instance, the explanation for the pattern of the scores on the scales in cluster 2 is somewhat speculative. Another interesting question to be answered is how teachers understand models and in what way the teachers are influenced by chemistry textbooks when teaching other topics. A study that investigates whether the results of the present study are applicable to teachers in other countries is also needed.

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Models in chemistry education

This thesis reports an investigation of how acid-base models are taught and understood in Swedish upper secondary school. Historically, the definition of the concepts of acids and bases has evolved from a phenomenological level to an abstract level. Several models of acids and bases are introduced in Swedish secondary school. Among them an ancient model, the Arrhenius model and the Brønsted model. The aim of this study was to determine how teachers handle these models in their teaching. Further, to investigate Swedish upper secondary students' ideas about the role of chemistry models, in general, and more specific, of models of acids and bases.

The study consisted of two parts. First, a study was performed to get an overview of how acids and bases are taught and understood in Swedish upper secondary schools. It consisted of three steps: (i) the most widely used chemistry textbooks for upper secondary school in Sweden were analysed, (ii) six chemistry teachers were interviewed, and, (iii) seven upper secondary school students were interviewed. The results from this study were used in the second part which consisted of two steps: (i) nine chemistry teachers were interviewed regarding their PCK of teaching acids and bases, and (ii) a questionnaire was administered among teachers of 441 upper secondary schools in Sweden.

The results show that most of the teachers did not emphasise a distinction between the various models of acids and bases in their teaching. For them it was sufficient to distinguish clearly between the meaning of acids and bases at the phenomenological level and at the particle level. A simple and valid argument for their preference was given: To simplify the acid-base concept and thereby facilitate learning. This study, however, shows that although students were expected to have learnt Brønsted's acid-base model, most of them had notdeveloped a clear picture of it.

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