Textbooks' and teachers' understanding of acid-base models used in chemistry teaching

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Abstract: Acid-base reactions can be described in several ways: by formula equations as reactions between substances, or by ionic equations as proton transfer reactions according to Brønsted's model. Both models are introduced in chemistry teaching at Swedish secondary schools. The aim of this study was to determine how textbooks and teachers handle the different models to explain acid-base reactions. First, chemistry textbooks most widely used in Swedish upper secondary schools were examined. Second, semi-structured interviews were conducted with six chemistry teachers. The textbooks neither described the differences between the models used to explain acid-base reactions nor clarified why the Brønsted model was introduced. Teachers were well aware of the importance of using models in their lessons. However, they seemed to have difficulties in applying this view with respect to acids and bases. There was no clear distinction between the models, some teachers had even not reflected on the differences between them. They seemed to rely on the content of chemistry textbooks. Implications for textbook writers, teachers and further research are discussed. [*Chem. Educ. Res. Pract.*, 2005, **6** (1), 19-35]

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Introduction

Studying science involves understanding the concepts that shape science. For teachers it is important to know how students interpret these concepts. Schmidt and Volke (2003) distinguished between the label/term and the content/meaning of a concept. Concepts that have a different meaning in science and in everyday life can confuse students (Pines and West, 1986). This can also happen with scientific terms that are used in different contexts because they have shifted their meaning in the course of the historical development (Schmidt, 1997). The concept *oxidation* is an example thereof. It can be defined with reference to the gain of oxygen (atoms) or to the loss of electrons. Here the content/meaning of the term is related to different models. Boulter and Gilbert (2000) considered it important for students to learn about models and their use but also to recognize their limitations. This would allow students to gain a better understanding of the subject and of how scientific knowledge is achieved. 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.

Models link theories with phenomena, they are part of theories scientists develop to explain phenomena that can be observed. Models used in chemistry can be both mental and more tangible instruments, such as ball and stick models, schematic pictures, diagrams or mathematical formulas. Each model emphasizes a specific part of the target only (Harrison and Treagust, 1998). A model should have the following characteristics (Van Driel and Verloop, 1999):

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

This study concentrates on different models used to explain acids and bases and how teachers and textbooks handle these models.

Background

Scientific background

The concepts of acids and bases belong to the basic principles of chemistry curricula. The way acids and bases have been explained has changed during the development of chemistry. New models are introduced trying to give a better description of reality. The alchemists defined acids on the basis of their sour taste. The way acids were explained developed stepwise until 1810 when Davy proposed that all acids contained hydrogen. The bases were still seen as neutralizers of acids, but a common composition was not known. At the end of the 19th century Arrhenius introduced the dissociation theory, for which he was awarded the Nobel Prize in 1903 (Arrhenius, 1903). He connected the acidic properties to positively charged hydrogen ions. Acids were defined as substances that produced H^+ ions in water solution. Bases were defined analogously as substances that produced OH^- ions. Using the Arrhenius' model, bases are limited to substances that contain OH groups. The Arrhenius model is also limited to water as a solvent. In the reaction between an acid and a base water is formed and – as a by-product – a salt. A reaction between hydrochloric acid and sodium hydroxide can be formulated like this (Arrhenius, 1903):

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

or simplified:

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

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 (molecules or ions). Acids are defined as particles that donate protons while bases are defined as particles that accept protons. Acids and bases exist side by side. Brønsted's acid-base definition is not limited to water as a solvent. When an acid donates a proton it becomes a base. 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. An acid and a base connected in this way are said to be a conjugated acid-base pair. A proton transfer according to Brønsted's model can be written like this:

(3) $acid_1 + base_2 \rightleftarrows base_1 + acid_2$

or:

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

To explain the basic properties of ammonia using the Arrhenius model, the existence of NH_4OH (although it does not exist) is assumed as an intermediate. It is formed in a reaction between water and ammonia:

(5) $NH_3 + H_2O \rightarrow NH_4OH$

In a second step NH_4OH dissociates producing OH^- ions:

(6) $NH_4OH \rightarrow NH_4^+ + OH^-$

A better explanation of the basic properties of ammonia in water can be given using Brønsted's model. Equation (7) illustrates how in an equilibrium reaction ammonia molecules accept protons from water molecules forming hydroxide ions:

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

Equations 1 and 2 suggest that acids and bases consume each other. A reaction between equivalent amounts of an acid and a base should, therefore, always result in a neutral solution. This is, however, not always true. If equivalent amounts of a weak Arrhenius-acid, e.g. acetic acid, react with a strong Arrhenius-base, e.g. sodium hydroxide, the resulting solution will be basic. This phenomenon can be attributed to the following proton transfer reaction (8), in which acetate ions and water molecules are in equilibrium with hydroxide ions and acetic acid molecules.

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

Brønsted's proton transfer definition 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. In 1954 Gutman and Lindqvist (Hägg, 1963) suggested another acid-base definition, in which the transfer of ions is emphasized. An acid is defined as a cation donor/anion acceptor and a base as a cation acceptor/anion donor. Here the Brønsted model can be seen as a special case, too, namely the transfer of cations in the form of protons.

Research literature

Previous research in science education shows how students (and teachers) struggle to understand the role of models in general as well as in chemistry to describe acid-base reactions. Justi and Gilbert (1999, 2000) reported that teachers used hybrid models instead of specific historical models in their teaching. Hybrid models result from a transfer of attributes from one model to another one. The authors also showed that many chemistry textbooks do not discuss why scientists use different models. Rayner-Canham (1994) stated that students must be clearly informed about the benefits of introducing a more complex model. Hawkes (1992) observed that the Arrhenius acid-base model confused students. When asked to use the Brønsted model, which applies to a variety of bases, students' thinking was still dominated by the Arrhenius model, in which only OH^- ion-producing substances are considered as bases. The author suggested that the Brønsted model should be introduced first, and that the Arrhenius model should only be used as a historical footnote. Demerouti et al. (2004) reported that students from upper secondary school were more familiar with the Arrhenius model; they did not use the Brønsted model to explain the properties of acids and bases.

Schmidt (1991) showed that students had difficulties understanding the concept of neutralization. Many students believed that any neutralization reaction would always result in a neutral solution. He attributed part of this difficulty to the ambiguous use of the term neutral in ordinary language and in the chemical context. Schmidt and Volke (2003) identified the mechanism students used to interpret the reaction from NO_3^- to NO in (9):

(9) $3Cu + 2NO_3^- + 8H_3O^+ \rightarrow 3Cu^{2+} + 2NO + 12H_2O$

"*First, oxide ions are released ... second these ions react with ...H_3O^+ ... forming water according to* ", (10) and (11):

(10) $NO_3^- + 3\ e^- \rightarrow NO + 2\ O^{2-}$
(11) $2\ O^{2-} + 4\ H_3O^+ \rightarrow 6\ H_2O$

In doing so students combined the redox reaction (10) with the acid-base reaction (11). Schmidt and Volke also found that students had problems accepting water as a base. Carr's (1984) study of chemistry textbooks showed that the books did not clearly distinguish between the Arrhenius and the Brønsted acid-base models. No explanation was provided why a new model was introduced and how a new model differs from the previous one. Oversby (2000) identified in a survey chemistry textbooks that explained different acid-base models but did not discuss the strengths and limitations of each model. 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.

Aim

Acids can take part in acid-base reactions and in redox reactions. Several models are in use to describe both types of reactions. The aim of the present study was to determine how chemistry textbooks and chemistry teachers handle different models used in schools to explain acid-base reactions. Data were collected by analyzing chemistry textbooks and interviewing chemistry teachers, having the following specific questions in mind:
How do Swedish upper secondary school textbooks and chemistry teachers

- introduce the acid-base concept
- present the neutralization reaction/acid-base reactions
- treat chemistry models in general
- treat models in the context of acids and bases

Method

The research process involved several steps. In order to define the area in which students' problems should be studied, multiple choice tests from Examination Boards in the US and the UK, dealing with acid-base reactions, were studied. In the next step chemistry textbooks commonly used in Swedish upper secondary schools were analyzed to see how they treat acid-base reactions. Interviews were then conducted with six upper secondary school chemistry teachers about how they introduce and present acid-base reactions, and how they use chemistry models in general and in the context of acids and bases.

Analysis of multiple choice tests from Examination Boards

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 based 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 analyzed the results of examination board tests to readjust the research questions.

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 – with the test statistics, i.e., the distribution of students' answers against the options (answer pattern), too. The multiple choice questions were stored in a computer file. 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 that asked simple questions, had an interesting answer pattern and contained some interesting incorrect answers. Three such questions are given as examples.

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 $H^+ + OH^- \rightarrow H_2O$. 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 student should chose among options that described the above statements as true. The majority of the students avoided all answer options where water was described as an acid.

Item 3: Students were asked to identify how nitric acid acts in the reaction with copper. A reaction equation was not given. Many students chose the option 'as an acid'.

We interpreted the results of the analysis of the examination board questions as follows.

- Item 1. Students preferred 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. 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. Students had not realized that in this case nitric acid acts does not act as an acid only, but as an oxidizing agent, too.

It was decided to use items 1 and 2 in the interviews with the chemistry teachers asking them to comment on the examination results.

Analysis of chemistry textbooks

In Sweden the acid-base concept is introduced at lower secondary level (ages 14-16) and further developed at upper secondary level (ages 17-19). At lower secondary level chemistry is taught with reference to phenomena. Reactants and products of chemical reactions are considered as substances, reaction equations written as formula equations.

(12) Acid + Base → Salt + Water

The formula equation can be seen as a simplified version – a *curricular model* – of the historical Arrhenius' acid-base model.

When students move from lower to upper secondary school – which are separate schools in Sweden – Brønsted's acid-base model is introduced. The Lewis model and other more advanced acid-base models are not taught in upper secondary schools.

The scope of the Swedish introductory course for upper secondary schools has recently been reduced. One of the main changes was that the chapter on chemical equilibrium was moved to the advanced course.

To find answers to the research questions the following four chemistry textbooks for upper secondary schools were analyzed: Andersson, Sonesson, Stålhandske, and Tullberg (2000), Borén, Larsson, Lif, Lilleborg, and Lindh (2000), Henriksson (2000), and Pilström, Wahlström, Lüning, and Viklund (2000). The final report was planned as a collection of 'stories' in the sense used by Kvale (1996). He described the qualitative researcher as a traveler to a foreign country telling stories when returning home (Kvale, 1996, p.4). To find the information needed the acid-base chapters of the books were analyzed about how they introduce and present the following concepts:

acid/ base
pH
acid-base reaction
redox reaction
neutralization
salt
acid-base models/theories
Brønsted's model/ theory

All reaction equations of the acid-base chapters were categorized with respect to the model they refer to:

Arrhenius model
Brønsted's model
hybrid between the two
redox model

The introductions to all books were read in order to see how they present chemistry models in general. For the same reason the contents of the books were searched via their indexes.

Interviews with chemistry teachers

Instead of drawing the teachers at random from a larger population, the interviewer (M.D.) invited six former colleagues who were known to have an interest in reflecting on and discussing teaching matters. This strategy has been discussed by Miles and Huberman (1994, p.268). All teachers had participated in evening lectures at the university in which results from research in chemistry education were presented. They were between 35 and 60 years old, all had at least 8 years of teaching experience and were teaching at four different upper secondary schools. Five of the teachers had masters' degrees. All of them used (like most other chemistry teachers in the area) Andersson's chemistry textbook (Andersson et al., 2000).

Semi-structured interviews were designed according to Kvale (1996). They consisted of three distinct phases: the briefing and warm up phase at the beginning, the main phase, and the debriefing phase at the end. Briefing and debriefing were not tape-recorded.

In the briefing phase the interviewer explained the purpose and the procedure of the interview (duration, use of audio recorder etc.). The teachers were asked for permission to use the tape recordings for research purposes and were assured about their right to withdraw from the interview at any time.

In the warm up phase certain parts of the chemistry curriculum the teachers liked and disliked were discussed. Teachers were also asked about how they tackled these parts.

In the main phase answers to the research questions were sought. Teachers were asked about how they introduced and presented the acid-base concept. It was discussed how they handled chemistry models in general and in the context of acids and bases. Teachers were also invited to comment on the textbooks. Finally, they were shown the first two of the multiple choice questions presented above and the test results from the examination boards to initiate a discussion about problems students may have to understand the chemistry of acids and bases.

During the debriefing phase, the research project was described more in detail. Teachers were given the opportunity to comment both on the content and the procedure of the interview. Teachers were again informed about their right to withdraw the permission to use the tape recordings for research purposes. The interview guide is presented in Appendix 1.

The interviews were transcribed in full. From the transcripts summaries of four pages per interview were written. The transcripts of the interviews and the summaries were read by both authors. They were first analyzed using a provisional list of categories that emerged naturally from the research questions and the interview guide (Miles and Huberman, 1994, p. 58). However, the interviews performed were semi-structured. This means that on the one side the questions used in the interviews were predetermined. On the other side the interviews were open for teachers' unexpected ideas, too. Therefore, some interview questions were added after the second and the fourth interview had been completed. The results of the interviews are presented in the form of eight 'stories' in the sense of Kvale (1996). Each story is given a specific headline (see the Result and Discussion section).

Results and discussion

Analysis of chemistry textbooks

The following 'stories' resulting from the textbook analysis consist of summaries followed by examples and discussions.

How textbooks introduce the acid-base concept

The book by Pilström (2000) introduces the acid-base concepts by defining acidic, basic and neutral solutions using the pH scale and indicators. Next, the book lists different acids and shows that all acids contain hydrogen. The Brønsted proton transfer reaction of acids in water is shown, followed by reactions of acids with non-precious metals. The book by Borén et al. (2000) introduces acids and bases by showing that all acids contain hydrogen. Several examples are given. Acid-base reactions according to Brønsted and redox reactions of acids with non-precious metals are discussed simultaneously. The books by Henriksson (2000) and Andersson et al. (2000) introduce acid-base chemistry by listing the properties of acids such as their sour taste and their reactions with non-precious metals. All books define bases according to Brønsted after the concept of acid was introduced. Bases and acids are, however, listed as substances. The books by Pilström et al. (2000) and Henriksson (2000) use both, the terms *bases* as well as *basic substances.*

Excerpt 1. Acid-base reactions and redox reactions of acids (Henriksson, 2000, p. 161).
"Reaction with carbonate
$CaCO_3(s) + 2H_3O^+(aq) + 2Cl^-(aq) \rightarrow Ca^{2+}(aq) + CO_2(g) + 3H_2O(l) + 2Cl^-(aq)$
After simplification
$CaCO_3(s) + 2H^+(aq) \rightarrow Ca^{2+}(aq) + CO_2(g) + H_2O(l)$
Reaction with non-precious metal
$Mg(s) + 2H_3O^+(aq) + 2Cl^-(aq) \rightarrow Mg^{2+}(aq) + H_2(g) + 2H_2O(l) + 2Cl^-(aq)$
After simplification
$Mg(s) + 2H^+(aq) \rightarrow Mg^{2+}(aq) + H_2(g)$"

The problems that arise when introducing the acid-base concept are manifold. No hints are given in the books that models are used to characterize acids and bases and to understand their properties. The readership is not informed that *different* models are used in parallel and why. The texts are not always clear about the model that is being used in a certain situation. Another misgiving arises from the formulation of the reaction equations. There is a difference between formula and ionic equations. Formula equations identify the *substances* that are involved when, for example, hydrochloric acid and calcium carbonate (13) or hydrochloric acid and magnesium (14) react with each other. Excerpt 1 refers to these reactions.

(13) $CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2\ (aq) + CO_2(g) + H_2O(l)$
(14) $Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$

Ionic equations name the *particles* that are involved in a reaction. Spectator ions are of no interest. The following equations (15) and (16) refer to the same reactions as (13) and (14).

(15) $CO_3^{2-}(aq) + 2H_3O^+(aq) \rightarrow CO_2(g) + 3H_2O(l)$ or
(15a) $CO_3^{2-}(aq) + 2H^+(aq) \rightarrow CO_2(g) + H_2O(l)$
(16) $Mg(s) + 2\ H_3O^+(aq) \rightarrow Mg^{2+}(aq) + H_2(g) + 2H_2O(l)$ or
(16a) $Mg(s) + 2H^+(aq) \rightarrow Mg^{2+}(aq) + H_2(g)$

Equation (15) illustrates how a proton transfer reaction between hydrogen ions and carbonate ions according to Brønsted takes place. Equation (15a) is a simplified version of (15). It will, however, not be easy to identify the proton transfer reaction that is mentioned in excerpt 1. Maybe the authors wanted to make the equations for acid-base and redox reactions as similar as possible

How textbooks present the neutralization reaction

Having discussed the concepts acids and bases, the books Andersson et al. (2000) and Henriksson (2000) explain the term neutralization. Henriksson (2000) informs the reader that this is a reaction in which H_3O^+ and OH^- ions disappear. Andersson et al. (2000) describe the neutralization as a water producing reaction. The authors mention, however, the formation of a salt, too. Borén et al. (2000) and Pilström et al. (2000) describe the neutralization reaction as a way to produce salts.

Excerpt 2. Reaction between sodium hydroxide and hydrochloric acid (Andersson et al. 2000 p. 112).
"$Na^+ + OH^- + H_3O^+ + Cl^- \rightarrow 2H_2O + Na^+ + Cl^-$
H^+

We can see that the ions Na^+ and Cl^- do not participate in the reaction. They are called counter ions or 'spectator ions'. Thus only the following reaction takes place.
$\underset{base}{OH^-} + \underset{acid}{H_3O^+} \rightarrow H_2O + H_2O$*"*

"The reaction between an acid and a base is called neutralization. A salt is formed."

Excerpt 3. Neutralization reaction (Borén et al., 2000, p. 90)
" In a neutralization reaction a salt solution is produced… If you neutralize e.g. sulfuric acid with a solution of potassium hydroxide, a potassium sulfate solution is obtained."

All textbooks claim that they use Brønsted's model to explain acid-base reactions. For Brønsted the neutralization reaction is a proton transfer between an acid and a base forming water (if water is used as solvent). The ionic equation (17) describes this aspect of the reaction properly.

(17) $H_3O^+(aq) + OH^-(aq) \rightleftarrows H_2O(l) + H_2O(l)$

A formula equation like (18) is, however, needed to illustrate that in a neutralization reaction a salt is formed, too.

(18) $HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$

All textbooks analyzed state that in a neutralization reaction an acid and a base consume each other. This is what the formula equation (18) tells us. However, in Brønsted reactions acids and bases never disappear. An acid reacts with a base forming another acid and another base – see equations (3) and (17). Two distinct models are needed to describe the different aspects of the reaction, but we found no discussion of that in the textbooks.

How textbooks use chemistry models in general

One of the books only describes the term model in the introduction. The book by Pilström et al. (2000) informs the reader that models are required to explain phenomena at the particle level. They are tools needed to "*work with what one cannot see*". Henriksson (2000) does not mention the term model in the introduction, but describes how, by inventing and testing a hypothesis, chemists produce new knowledge.

All textbooks present pictures of ball-and-stick molecular models. In this context the term model is named, but not discussed.

In three books the term model is mentioned in connection with atomic models. Only two of the books, however, namely Pilström et al. (2000) and Henriksson (2000), really explain how these models can be used. In the book by Andersson et al. (2000) the term model is mentioned in this context, but not explained.

How textbooks use models in the context of acids and bases

The book by Pilström is the only one describing the history of the acid-base models (Pilström et al., 2000, p. 204). The other books do not mention the different models.

Excerpt 4. Acid-base reactions (Pilström et al., 2000).
"When gaseous ammonia is dissolved in water, some of the ammonia molecules will react as follows:

$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$*"* (p. 55).
H^+

"If you mix hydrochloric acid with a solution of sodium hydroxide, the hydrogen ions react with the hydroxide ions in the hydroxide solution according to the equation $H^+ + OH^- \rightarrow H_2O$…" (p. 56).

Although in the book by Pilström et al. (2000) several acid-base models are mentioned, the authors are not clear about which model they refer to at a certain moment in the text.

All the books analyzed, describe the Brønsted model as if no previous models existed.

Interviews with chemistry teachers

The following 'stories' resulting from the interviews consist of short summaries from the transcripts, followed by excerpts from the interviews and discussions of the results. In the excerpts the interviewer is indexed 'I' while the teachers are indexed T1, T2 ... T6.

The parts of the curriculum the teachers liked and disliked

The teachers named *various* parts of the curriculum as their favorites: stoichiometry, physical chemistry, organic chemistry, biochemistry, or redox chemistry. However, they had two reasons only for their preferences: teachers felt (1) they were knowledgeable in the particular field, or (2) they could easily connect that part of the curriculum to situations in everyday life.

T5. During my chemistry studies I concentrated on analytical and physical chemistry so I guess that's why I especially like physical chemistry. It's because I know it so well.

T4. I usually ask the students what they think about my teaching and they say that everyday applications are very important.

The parts of the curriculum the teachers did not like to teach were: electrochemistry (two teachers), biochemistry (two teachers), organic chemistry (one teacher) and acid-base chemistry (one teacher). Teachers had two reasons for their misgivings: they felt these parts of the curriculum were (1) too abstract and difficult, or (2) too easy, students would not profit from them.

T4. Electrochemistry. Students think it's very difficult and abstract. They also tend to confuse galvanic cells and electrolysis. This part is very theoretical and the demonstrations are difficult for students to understand.

T1. The acid-base part has become superficial. It's what you have already done at the lower secondary school, and you don't get any further or deeper. There are a couple of pages with properties of some acids and what will dissolve in them, general chemistry, only what's happening and no explanations why. Students don't see this as knowledge, just as a lot of facts. You don't get much out of it.

The strategies teachers used were the same for all parts of the curriculum and did not depend on their preferences.

Teachers' attitudes and expectations towards teaching acid-base chemistry

Five teachers enjoyed teaching acid-base chemistry and felt that students would understand this part of the curriculum easily. One teacher said that teaching acids and bases at upper secondary level would repeat what has already been taught at lower secondary level. The teachers expected their students to have problems only with understanding stoichiometric calculations, logarithms (pH) and buffer solutions.

T6. This part is easy to teach, students already know a lot. They want to know more…e.g., calculate the pH of weak acids.

I. What do you think are the main difficulties for students in this part?
T2. It's logarithms, because they don't know enough math yet. Then you have to explain it, and since I'm also a math teacher I know some ways to explain it 2-3 ways, but it's 10^{-pH}, what's p, what's log, is pH a concentration?
I. You think that the students' problems are mostly mathematical?
T2. Yes, and then we have concentrations. Students must distinguish between HCl and H_2SO_4 and also mole proportions.

None of the teachers were aware that students could have difficulties in applying formula and ionic equations to acid-base reactions and to understand the related acid-base models.

How teachers introduced acid-base reactions

Four teachers introduced the acid-base concept listing acids and bases that students know from everyday life. Writing chemical formulae students were expected to see that all acids contained hydrogen. Acids were then defined as substances that when dissolved in water produced hydrogen ions. Later, pH values of acidic solutions were determined and related to the concentrations of hydrogen ions. Two teachers introduced the acid-base concept measuring the pH of various acidic solutions. Students were told the pH to be a measure of the hydrogen ion concentration. Similar experiments were conducted with basic solutions.

T4. I always start from everyday life. What is an acid and what is a base? We show them, so the students can smell, feel and taste. …Then you can go on and apply this to the human body. What will happen if this gets into our body? Which are more dangerous, acids or bases? That's how I introduce it.

All teachers defined acids and bases as *particles* taking part in proton transfer reactions. However, they showed students *substances* as examples for acids and bases.

How teachers presented the neutralization reaction

All teachers discussed with their students the neutralization reaction. Strong acids were titrated with strong bases as a laboratory experiment. All teachers emphasized that in this reaction water and salt were formed. Three teachers demonstrated in comparison titrations with weak acids or bases, too. However, the focus was still on the formation of salt.

T3. The students perform the titrations with strong acids and bases themselves. Then I demonstrate a titration of a weak acid.
I. How do you compare the results? Do you draw titration curves?
T3. No, not in the introduction course. We just look at the formation of salt ... and water of course.

All teachers claimed that they used in class the Brønsted model to interpret acid-base reactions. Discussing the neutralization reaction, however, they referred to reaction equation (12).

How teachers used chemistry models in general

All teachers agreed that it was important for students to know that chemistry deals with models. They admitted they had not discussed this aspect satisfactorily with their students.

T1. I try to discuss models and why we use models with the students. It's difficult to make the student understand that we deal with models. They are inclined to believe we deal with the truth.

T2. I try to explain the use of models right from the start. This is the model we use right now since we can understand it. Later on, when we know more physics and mathematics, we can move on to other models.

How teachers used models in the context of acid-base chemistry

Teachers had difficulties applying their general view of models to acid-base reactions. In their view the Arrhenius and the Brønsted acid-base definitions did not count as models.

I. Can you give me examples of models you use?
T2. Yes, Bohr's atomic model.
I. Do you use models in the acid-base part as well?
T2. Yes …We use ball-and-stick molecule models sometimes.

In addition, teachers had difficulties to see the differences between the models.

T3. This about a proton, a hydrogen ion, and an oxonium ion. Not all students understand that it's the same.

T3. They have problems realizing that there's no reaction with sodium hydroxide in water. It's a queer element that it only dissolves as compared with ammonia.

I. What do the students think about writing acid-base reaction equations?
T5. That they learn quickly that water is formed in a neutralization reaction … and a salt.
I. But if you dissolve ammonia in water, you don't get water and salt.
T5. No, that's protolysis in water. Water is the acid and isn't formed.
I. Do you see this as a different model for explaining an acid-base reaction?
T5. No … I haven't thought about it that way. Water can't be formed if it participates in the reaction as an acid or base.

The teachers were aware that the *Brønsted* and *Lewis* definitions of acids and bases are related to different models. These are the ones they will have met in their teacher training at University. This may be the reason why they did not recognize previous models.

Teachers' comments on the chemistry textbook

All teachers used Andersson's textbook (Andersson et al., 2000). Two teachers used in addition examples from other textbooks, but the book by Andersson et al. (2000) was the main source for the students. Two teachers did not like how redox reactions of acids are presented and excluded these parts of the book from their lessons. Teachers felt that the textbook was simple and accessible. They said that their students appreciated the book highly because of the summaries in the margin. One teacher thought the textbook was so clear presenting acids and bases that he had used it as a self-study material for the students.

T2. If the students miss a lesson, they can easily read it themselves. Last year I asked them to read a chapter on their own. I chose the acid-base chapter since it's relatively easy and the students at that point have been through a major part of the chemistry course. I think the book explains it well.

T5. Students like the book. It's a good thing it has summaries in the margin.

Since the teachers were not aware of the different acid-base models, they had not noticed that the textbook did not clearly distinguish between them. They perceived the book to be quite clear in this respect. Two of the teachers noticed that the book discussed acid-base reactions and redox reactions of acids simultaneously.

Teachers' comments on the multiple choice tests

Teachers were surprised about students' answers to the multiple choice questions. Two statements occurred repeatedly:

Item 1
T5. You focus on what's formed, not on what really happens.
T1. You forget about the counter ions. You teach that in the beginning of the course but then you forget about it.
Item 2
T4. Maybe you shouldn't emphasize that acids and bases are dangerous substances
T3. The students should know that water is an ampholyte.

The discussion with teachers showed: they realized that students could have difficulties to understand what was taught in class.

T5. I've never thought of it this way. It makes sense. I'll have to check the book more closely.

Teachers may have felt uncomfortable during the interview when their teaching was questioned (Kvale, 1996, p. 128). In order to minimize this tension, the interviewer explained that the research questions were developed from examination questions. The discussion of the results of the examination tests offered an opportunity to discuss students' problems understanding acid-base chemistry in general. Teachers thus realized that other students had the same problems in this field. The discussion about the multiple choice items continued in the debriefing phase.

General discussion

Research has shown that textbooks play an important role for teachers planning a lesson. Tobin, Tippins, and Gallard (1994) reported that when "*planning science programs, teachers partitioned the year's work into topics to be covered each term and subsequently planned the content to be covered each week and in each lesso*n" (p. 51). It seems that for the teachers participating in the present study the chemistry textbook was an important source of information, too.

In our study the analysis of the textbooks and the interviews revealed that the acid-base concepts presented by the books and by the teachers were the same. Acids and bases were introduced as substances. Later the Brønsted model was used. Most textbooks and all teachers mentioned the formation of salt when talking about the neutralization reaction. It is reasonable to introduce acids and bases at the phenomenological level as substances that consume each other. This interpretation of a neutralization 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.

Research has shown that teachers were aware that different models exist but did not use them in their classes (Justi and Gilbert, 2002). The same was observed in the present study. The teachers were well aware of the importance of models but had difficulties to make use of them to explain the properties of acids and bases. Textbooks and teachers neither described the differences between the models nor clarified why the Brønsted model was introduced. Some teachers had not even commented on the differences between them. Most teachers claimed they taught the Brønsted model, but they also used previous models simultaneously.

The interviews showed that teachers did not realize that their textbook did not clearly distinguish between Brønsted's and previous models. They may not have recognized older models because they only met the Brønsted and other modern acid-base models at university.

We expect other researchers to arrive at similar results interviewing teachers in Sweden. There are two reasons for it:

(1) What teachers told us during the interviews was similar to what was described in their textbook. This can easily be explained assuming that the textbook they relied upon had influenced the teachers. Our textbook analysis was based on books that are commonly used in Sweden. It is, therefore, reasonable to expect that the books will influence other teachers in the same way.

(2) Teachers selected for the interviews were known to have an interest in reflecting on their teaching. The present study shows that even these teachers were not clear about the use of acid-base models. If these teachers did not think about the use of models this may apply even more to ordinary teachers.

Perhaps the situation observed in Swedish schools can also be seen in other countries. The following observations may illustrate our expectations. One important goal of Nuffield Chemistry, the famous British curriculum development of the 1960s, was helping students to develop relationships between experimental results and "*explanations in terms of a model*" (Nuffield Foundation, 1968, p. 7). With respect to acid-base chemistry the *Handbook for Teachers* states: "*… when pupils ... know how to represent what is going on at a molecular level ... (they) are then ready for a simple form of Lowry-Brönsted approach*" (Nuffield Foundation, 1969, p. 31). However, a more detailed analysis of this aspect is missing. In 1977 Keller, a well-known chemistry educator from Germany, published a book about models in chemistry teaching (Keller, 1977). Under the heading *Models used in relation to chemical reactions,* the Brønsted concept is mentioned (p. 33), but not discussed in detail.

Finally, the observation that the textbooks failed to discuss the different models used to describe acid-base reactions is not intended to imply that the textbook authors are unaware of these models. In discussions the textbook authors gave a simple and valid argument for the chosen presentation of the acid-base concept: to simplify it and thereby facilitate learning.

Implications for teaching and research

The results of the present study emphasize 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. They should help students 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. In this context a distinction between formula and ionic equations has to be made. To identify some key points:

Acids and bases are introduced as substances referring to students' experience from everyday life. In an acid-base reaction acids and bases consume each other forming salt and water. Formula equation (18) describes the reaction between hydrochloric acid and sodium hydroxide properly at the phenomenological level.

Brønsted defines acids and bases as particles. In an acid-base reaction an acid reacts with a base forming a new acid and a new base. The formation of salt (and water) is *not* a prerequisite of a Brønsted acid-base reaction. The ionic equation (17) illustrates what 'really' happens in a neutralization reaction. However, (17) does not tell us *which* substances react with each other.

Teachers should also expect their students to have difficulties classifying water as an acid or a base. In the reaction between ammonia and water, ammonia molecules accept protons from water molecules and, therefore, act as a base (7). Water molecules donate protons and act as an acid. In this Brønsted acid-base reaction neither a salt nor water is formed.

Acids do not only react with bases, but also with (certain) metals. This phenomenon is often presented to students when introducing the concepts acid and base. The present study revealed that textbooks (and teachers) should clearly describe the differences between acid-base and redox reactions. Formula equation (14) refers to the reaction between hydrochloric acid and magnesium, naming all reactants and products. The same is true for equation (18) illustrating the reaction between hydrochloric acid and sodium hydroxide. It may be reasonable for upper secondary school courses to describe (14) as an electron-transfer reaction using the ionic equation (16), and (18) as a proton transfer reaction using the ionic equation (17).

The recommendations mentioned here could be used in chemistry lessons helping students to "*gain an understanding ... of what it means to approach a problem scientifically*", (Nuffield Foundation, 1968, p. 1).

The teachers interviewed used their chemistry textbooks to prepare their lessons. They had, however, not noticed that their textbooks did not clearly distinguish between the different acid-base models used in school. Teachers should be more critical when reviewing textbooks.

More research is needed for a better understanding of the role of acid-base models in teaching and learning. During the interviews teachers described how they taught acid-base chemistry. From the results, however, we do not know what really happened in the classroom. We also do not know how Swedish students apply their general view of models to other concepts in chemistry. Another interesting question to be answered is how *students* understand acid-base concepts and models and in what way they are influenced by chemistry textbooks. An investigation of this type is under way. A study that clarified whether the results of the present study are applicable to students in other countries is needed too.

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Appendix 1

Interview guide

- Introduction
  - Presentation: About the interviewer and the research project
  - Permission to use tape recorder
  - Questions from interviewee; regarding the interview procedure

- Briefing
  - Teaching experience, years, and schools?
  - Favourite domain in chemistry
    - Why is it your favourite?
    - How do you introduce / teach it?
    - What do students think about it?
  - Are there other domains you do not like to teach?
    - Why do you dislike them?
    - Are there any differences in the way you teach them compared to the one above?
    - How do you introduce / teach them?
    - Do you think the book is clear in this domain?
    - What do students think about this domain?

- Main Phase
  - I would now want to talk about acids and bases. What is your opinion about this part?
  - Do you think it is easy to teach?
  - In your opinion, what problems do students have in understanding acids and bases?
  - How do you introduce acids and bases?
    - Do you use Brønsted's definition?
    - How do you move on?
    - How do you explain acid-base reactions?
    - How do you write equations?

(acid + base $\rightarrow$ salt + water; $\text{acid}_1 + \text{base}_2 \rightleftarrows \text{base}_1 + \text{acid}_2$)

    - Do you see them as several models?
  - Do you discuss the use of models in chemistry in general?
  - Do you discuss the differences between acid-base reactions and redox reactions of acids?
  - Which textbook do you use? Do you find it clear with respect to acids and bases?
  - Do you have any experience from the previous chemistry courses and previous books? What is better now and has anything become worse?
  - How does the book use and explain the use of models in chemistry?
  - Presentation of multiple choice questions
    - Explain the research project in detail. Our conclusions from the multiple choice questions. Discuss the different models related to acid-base chemistry.

- Debriefing
  - I have no further questions. Questions from the interviewee, permission to use the recording, discuss some points of the interview.