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Upper Secondary School Students' Understanding of Models Used in Chemistry to Define Acids and Bases

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ABSTRACT *The concepts of acids and bases belong to the basic principles of chemistry. In Swedish schools, these concepts are introduced as substances and further developed using the Brønsted model that refers to particles. Research indicated that textbooks authors and teachers who took part in the investigation were not aware that at this level different models exist to explain acid-base reactions. Thus, teachers taught and textbooks presented the Brønsted and older models simultaneously. Seven semi-structured interviews were conducted to investigate the ideas Swedish students from upper secondary school had about the role of chemistry models in general and those related to acids and bases. The results showed that students were also familiar with the Arrhenius model. They had, however, difficulties to properly describe acid-base reactions using the Brønsted model. They were aware of the importance of using models in chemistry in general, but could not apply their views to acid-base reactions. Implications for teaching and further research are discussed.*

KEY WORDS: *Acid-base reaction, Brønsted model, Arrhenius model, semi-structured interview*

Introduction

Learning science involves understanding the concepts that shape science. Research on students' understanding of concepts in science has been recognized as one of the major fields in science education. Trying to understand scientific concepts students often form their own ("alternative") concepts (Pines & West, 1986). Schmidt and Volke (2003) distinguished between the label and the content of a concept. A concept can mean a category of similar phenomena sharing certain attributes. The concept 'oxidation,' for example, involves all oxidation reactions. It can also contain a theory or an explanation of a phenomenon. Thus, the concept 'oxidation' can be explained by electron transfer between particles (Eybe & Schmidt, 2004). Models link theories with phenomena and are part of theories, while in research scientific consensus models are used. Curricular models are simplified versions of scientific models used in school (Van Driel & Verloop, 2002). "*Modelling is a powerful skill that defines much of the scientific method*" (Harrison & Treagust, 1996, p. 509).

The label of a concept can refer to several explanations (models), e.g., the concept 'oxidation' can refer to the gain of oxygen atoms, the loss of electrons, or the increase in oxidation number (Schmidt, 1997). The existence of *multiple* models to explain *one* concept may confuse students. The concept 'oxidation' is a good example to show that in the course of their historical development the content of the label changed, whereas the label stayed the same. Schmidt and Volke (2003) attributed many of the problems students encounter to this shift of meaning. Research also reported that students trying to arrive at a unified model combined attributes from different models (Justi & Gilbert, 2002). The present study concentrates on students' understanding of models used to explain acid-base reactions.

Scientific background

The concepts of acids and bases have evolved from phenomenological to abstract definitions. On the phenomenological level, they can be defined in terms of their properties: aqueous solutions of acids turn blue litmus red, neutralize bases, etc. Bases can also be defined accordingly. Neutralization is seen as a reaction between substances and represented by a formula equation:

(1) acid + base $\rightarrow$ salt + water

In 1887 Arrhenius proposed that the properties of acidic solutions were due to the presence of H^+ ions, and the properties of basic solutions to OH^- ions. Acids were seen as substances that contained hydrogen, bases as substances that contained hydroxide. In a reaction between an acid and a base - neutralization – hydrogen ions from the acid react with hydroxide ions from the base forming water (Arrhenius 1903):

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

or simplified

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

The Arrhenius model refers on one side to substances (phenomenological level), on the other to particles (particle level). Equation (3) tells us what really happens in a neutralization reaction.

In 1923 Brønsted and Lowry defined acids and bases on the particle level as proton donors and proton acceptors. 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. A proton transfer according to Brønsted can be written in general terms like this:

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

or as an ionic equation:

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

Reactions (4) and (5) show that in a Brønsted proton transfer reaction, acids and bases never disappear.

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 can, therefore, not be labeled an Arrhenius base. Equation (6) illustrates, however, that NH_3 molecules accept protons:

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

NH_3 is, therefore, a Brønsted base. Equation (6) illustrates that the formation of water or salt is not necessarily a prerequisite for a Brønsted acid-base reaction.

Equations (1) and (2) suggest that in a neutralization reaction, acids and bases consume each other. The result is a neutral solution. This is, however, not always true. Neutralization reactions between weak acids like acetic acid (HAc) and strong bases like sodium hydroxide (NaOH) yield basic solutions. This phenomenon can be attributed to a reaction between acetate ions and water molecules (7).

(7) $Ac^- + H_2O \rightleftarrows OH^- + HAc$

Brønsted's model can be seen as a special case of the more general Lewis model where acids and bases are defined as electron pair acceptors and donators.

Research literature

Several studies showed that students had difficulties understanding the concepts acid and base. Cros et al. (1986) reported that university students tended to use descriptive definitions of acids and bases such as $pH < 7$ or $pH > 7$. They also had problems identifying bases. Ross and Munby (1991) found that upper secondary students had difficulties in describing bases on the particle level. Schmidt (1991) showed that students had problems understanding the concept of neutralization. Many students believed that any neutralization reaction would always result in a neutral solution. Rayner-Canham (1994) observed that many students enter college courses with a strong belief in the Arrhenius theory of acids and bases. Hawkes (1992) noticed that students, when asked to use the Brønsted model, were dominated by the Arrhenius model, in which only OH^- ion-producing substances are considered as bases. He suggested that teaching should concentrate on the Brønsted model, but discuss the Arrhenius model only as a historical footnote. It was also reported that upper secondary school students had difficulties understanding conjugated acid-base pairs (Schmidt, 1995). Schmidt and Volke (2003) found that upper secondary students had problems accepting water as a base. 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. Carr's (1984) analysis of chemistry textbooks showed that the books did not clearly distinguish between the different acid-base models. It was not typically explicated when and why a new model was being used. Drechsler and Schmidt (2005) analyzed chemistry textbooks and interviewed teachers from upper secondary schools, and found that neither the books nor the teachers in their lessons clarified that different acid-base models exist. The teachers claimed they taught the Brønsted model, but used previous models simultaneously.

Aim

The concepts of acids and bases belong to the basic principles of chemistry curricula. There are two reasons for it. (1) Acids and bases are recognised from everyday life in the contexts of food digestion, acid rain, food preservatives, soft drinks, corrosion, and drugs. (2) Chemistry like any other science deals with models. They are used in the research process to explain and predict phenomena and to test hypotheses. It is, therefore, important for students to learn about models and how they are handled (Boulter & Gilbert, 2000). In acid-base chemistry, several models are in use.

An interview study was planned to investigate students' ideas about the role of models in general, and how models are applied to acids and bases. The specific research questions were:

How do Swedish secondary school students understand:

- the concepts acid and base?
- acid-base reactions?
- the role of models used in chemistry in general?
- the role of models used in the context of acids and bases?

Method

The research process involved two steps. First, in order to define the area in which students' problems should be studied, multiple choice tests, from Examination Boards in the UK, dealing with acid-base reactions were studied. Second, interviews were conducted with seven students.

Examination Board Tests

The analysis of the results of the Examination Board tests formed the basis to develop the interview guide. Examination Boards usually do not publish exam questions and test results. However, several boards in the UK provided us with test items for research purposes. Their analysis leads to two multiple choice items that asked simple questions and contained some interesting incorrect answers. These were used in the interviews.

***Item 1*:** Students were asked to identify the reaction equation that would most adequately describe the reaction between dilute hydrochloric acid and aqueous sodium hydroxide. The following options were given:

A. $H^+ + OH^- \rightarrow H_2O$

B. $Na^+ + Cl^- \rightarrow NaCl$

C. $NaOH + HCl \rightarrow Na^+ + Cl^- + H_2O$

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

E. $Na^+ + OH^- + H^+ + Cl^- \rightarrow H_2O$

Students preferred B and D as incorrect answers.

***Item 2*:** Students were asked whether in the equilibrium

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

A. NH_3 acted as a proton acceptor

B. H_2O acted as an acid

C. OH^- acted as a base

Students preferred combinations in which water was *not* an acid.

Obviously students preferred reaction equations that name salt or water as a product of an acid-base reaction (Item 1). They also had difficulties to accept water as a base (Item 2). In conclusion, students seemed to be more familiar with the Arrhenius than with the Brønsted model.

Interview Sample

In Sweden, the concepts of acids and bases are introduced at lower secondary school level (ages 14-16) and further developed at upper secondary school (ages 17-19). At upper secondary level, acid-base chemistry is taught in an introductory and an advanced course. For the interviews, students from upper secondary schools, who had completed the two courses and who ranked at the top of their chemistry classes, were invited. "This measure was taken in order to find interviewees who might be more willing to discuss chemistry problems in a reflective way" (Miles & Huberman, 1994, p. 268).

Teachers who volunteered students from their classes were employed at three different schools in central Sweden. They were former colleagues of the interviewer (first author). The teachers were asked to select top students on the basis of their chemistry achievements. Seven students (3 girls and 4 boys) took part in the interviews. All students were indeed high achievers in chemistry and wanted to continue their education at university. They had used their chemistry textbook regularly and completed all the exercises. Two students had also used extra-curricular books to improve their understanding, especially in areas that were not clearly explained in their "official" textbooks. Students were interviewed in their schools for 45 to 60 minutes.

Design of the Interviews

A guide for a semi-structured interview was developed according to Kvale (1996). The interviews consisted of four phases: a briefing phase, a warm-up phase, a main phase, and a debriefing phase. Briefing and debriefing were not tape-recorded. The briefing phase consisted of a short presentation of the project and the interview procedure was discussed (duration, use of tape-recorder, etc.). Each student was asked for permission to tape-record the interview and use the recording for research purposes. The students were informed that they could withdraw their permission to use the recordings at any time. In the warm-up phase, general questions were asked about which areas of the chemistry curriculum students liked and which they found difficult. In the debriefing phase, the research project was described in more detail. The students had the opportunity to ask questions of any kind. Students could comment on the interview itself and how they felt during the interview. Once again, they were informed about their right to withdraw the permission for the researcher to use the tape recordings.

In the main phase, students were asked how they liked the acid-base chapter and how they understood acid-base reactions. They were invited to solve items 1 and 2, and to comment on the exam results. Their understanding of chemistry models in general, and in the context of acids and bases was questioned.

On completion of each interview, the interviewer took notes on the aspects that the tape-recorder could not document, such as statements from the students in the debriefing phase, the atmosphere during the interviews, and students' behavior. The interview guide is presented in Appendix 1.

Analysis of the Interviews

The interviews were tape-recorded and transcribed. After every second interview, the interview guide was revised. Each interview transcript was collated into four pages. These were analyzed using a provisional list of categories (see Appendix 1) that emerged naturally from the research questions and the interview guide (Miles & Huberman, 1994).

Results and Discussion

In this chapter, excerpts of students' responses to the interview questions are presented. The excerpts are translations from Swedish. In the text, the interviewer is indicated as I, and the students as S_1-S_7. A description of how a student changed his ideas during the interview was added to the categories that were originally planned.

Warm-up Phase

Students liked and disliked different areas of chemistry. Their favourites were organic chemistry (one student), bio-molecules (2 students), biochemistry (one student), stoichiometry (one student), physical chemistry (one student), and electrochemistry (one student). They liked a unit because it could either be linked to everyday life or was thought to be intellectually fascinating, and gave new insights into how matter works. The areas of the course students did not like were acid-base chemistry (four students), biochemistry (one student), stoichiometry (one student), and electrochemistry (one student). Students thought these areas were too difficult, abstract, or unstructured.

Main phase

Students' Reflections on Acids and Bases

In the interviews, students were asked what they remembered about acids and bases. In their answers students referred to: the pH-scale, indicators, violent reactions, changing ideas about the term acid, acids as proton donors and bases as proton acceptors.

> *(S_5) The acid-base area was neither boring nor too difficult...but the concepts had changed compared to what they meant from the beginning. First, you learned one thing, and then this was extended so that an acid can also be a base.*

> *(S_6) When you dilute an acid, it is important to pour acid into water and not the other way round, or else it can result in a violent reaction...And then, I remember that it all changed. In a reaction there is always one acting as a base. Even if you have two acids, for example HCl and H_2SO_4, one is a base.*

> *(S_7) Acids and bases are very difficult for me...Acids donate protons and bases are substances that accept these protons. It is pretty tricky, because, if you look at water, it is both an acid and a base. If a water molecule is first a base, it takes a proton from another water molecule, so that the water molecule that was first a base suddenly becomes an acid. It is quite difficult to keep up with that, how it turns around.*

Students' Understanding of Acid-base Reactions

Four students said in the interviews that in an acid-base reaction acids and bases consume each other. If, therefore, acids and bases react in equivalent amounts, the resulting solution is neutral. In doing so, these students concentrated on the formation of water.

> *(S_1) In an acid-base reaction the result will be neutral... They consume each other depending on their concentrations. Hydrogen ions or oxonium ions and hydroxide ions form water in a neutralisation.*

S_1 formulated the equation for the reaction between acetic acid (HAc) and sodium hydroxide (NaOH) like this:

(S_1) HAc + NaOH $\rightarrow$ *NaAc +* H_2O, *and* concluded:

(S_1) Since water is formed, it becomes neutral.

S_5 wrote the equation for the reaction between hydrochloric acid and sodium hydroxide as follows:

(S_5) HCl + NaOH $\rightarrow$ *NaCl +* H_2O, and concluded:

(S_5) In an acid-base reaction, it becomes neutral.

Asked about acid-base reactions, S4 immediately remembered the transfer of protons.

(S_4) What comes to my mind first are proton donors and proton acceptors.

He used the equation *(S_4)* $B + H_3O^+ \rightarrow BH^+ + H_2O$ to describe the reaction in general terms. In this equation, B symbolizes *any* particle that would accept a proton. However, H_3O^+ ions are seen as the only particles being able to *donate* protons. The following excerpt demonstrates how the student struggled to understand the proton transfer between particles other than H_3O^+- (H^+-) and OH^- ions.

(I) What is the acid and what is the base in your equation?

(S_4) H_3O^+ *is the acid and B is the base.*

(I) What can you say about the products?

(S_4) One has accepted a hydrogen and is now positive. The other has donated a hydrogen and is now neutral.

(I) Can you tell me anything more?

(S_4) Yes, there is a change of charges among the protolytes.

(I) If you should write the reaction in words, how would you do it?

(S_4) base + acid $\rightarrow$ *baseH + acid-H (acid minus H), I do not know, this is difficult.*

(I) Why is it difficult?

(S_4) I do not know, I have never thought about it this way.

(I) If you should write the reaction between hydrochloric acid and sodium hydroxide in words, how would you do it?

(S_4) That is easier ($H^+ + OH^- \rightarrow H_2O$) *acid + base* $\rightarrow$ *water.*

(I) Do you see any differences between these two reactions?

(S_4) No.

Arriving at that point where the student could use the Arrhenius model to describe a neutralization reaction – a special proton transfer – S_4 seemed to be satisfied. The comments, however, do not suggest that he understood the Brønsted model as well.

S_7 and S_2 tried to explain acid-base reactions via proton transfer, too. In doing so, S_7 defined HCl as the acid and NaOH as the base.

(S_7) $HCl + NaOH \rightarrow NaH_2O + Cl^-$. *HCl is the acid and NaOH is the base.*

(I) What do you think when you write this equation?

(S_7) I think that a proton is transferred from the acid to the base.

He was doubtful about this reaction equation but could not find a better alternative.

S_2 described the reaction between HCl and NaOH in water as a reaction between H_3O^+- and OH^- -ions.

> *(S_2) HCl and NaOH will be protolysed in water, and H_3O^+ and OH^- ions are formed. An equilibrium with water is established and the reaction keeps moving back and forth.*

Students' Responses to Multiple Choice Item 1 (MC1)

Students were asked to answer Item 1. They selected several alternatives. S_2 arrived at the correct answer A. He realized that the equation presented properly described a reaction between an acid and a base without mentioning the spectator ions.

S_4, S_5 and S_6 preferred distractor C. They saw that in the equation, the formulae of the reactants HCl and NaOH were given. Students also felt that the equation did *not* describe sodium chloride as a precipitate (as in B and D).

S_3 and S_7 arrived at distractor D. The reason was that in the corresponding equation the formulae of the reaction products were presented. In addition, students said that the equation properly described the reaction between H^+- and OH^- -ions forming water.

For student S_1 the options A, C, and D were equally attractive. She identified H^+ as well as HCl as acids and OH^- as well as NaOH as bases.

Students' Responses to Multiple Choice Item 2 (MC2)

Students were also asked to answer Item 2. All of them identified every statement as correct. However, S_1, S_2 and S_7 were reluctant to call water an acid.

> *(S_1) It is difficult to think about water as sour...*
>
> *(S_2) Because water is not really...it is both an acid and a base as I recall it...but... I do not know...water is water, right? It makes me think of something neutral, something that is not extreme in any way.*
>
> *(S_7) You can't imagine drinking an acid, but you drink water.*

S_5 confused the concepts acid and sour as well as base and basic. She identified ammonia as a base and water as an acid, but the ammonium ion as sour and the hydroxide ion as basic.

Students' Understanding of the Use of Models in Chemistry in General

All students agreed that chemistry deals with models. For them models were tools to explain observations. In research, models are used to test hypotheses. Students saw models as simplifications of reality and a means to link theories with phenomena. The interviews also showed that models had been discussed in class only in the introductory lessons and as atomic models.

Students Understanding of Models in the Context of Acids and Bases

Students did not realize that several models are available to explain acid-base reactions. Confronted with the equations (1) acid + base $\rightarrow$ salt + water and (4) $acid_1 + base_2 \rightleftarrows base_1 + acid_2$, some students argued that both equations contained the same information. Since water was neutral, but could nevertheless act as an acid or a base as well; students assumed that this was true for a salt as well.

(S_1) In MC2 it becomes basic but in MC1 it becomes neutral, but it is still an acid and a base. NaCl is fairly neutral, since we have it in our body.

(I) You simplified the two reactions to: acid + base → salt +water and

acid + base → base + acid, respectively. Did I understand you correctly?

(S_3) Yes.

(I) There are some differences between these two reactions. How do you explain them?

(S_3) Some substances, e.g., water, can act both as an acid and as a base depending on the substance with which they react.

(S_5) Salt and water are formed… there should be an acid and a base as well…perhaps you can identify NaCl as an acid, I am not too familiar with that.

At the end of the interview, the different models were explained to the students. Some of them said it would be better to learn the Brønsted model only.

(S_4) It would have been better to learn Brønsted from the beginning. It gets messy to change models when you've already learned it one way.

Students' Changing Ideas During the Interview

During the interview, several students trying to make sense of the concept acid and base changed their minds. In the discussion with S_7, this was most obvious. When explaining the reaction between hydrochloric acid and sodium hydroxide, S_7 tried to apply the proton transfer model first, but solving MC1 used a formula equation. Confronted with this behaviour, he put forward a third idea based on the attraction between ions.

(I) What do you remember about acids and bases?

(S_7) …Acids are those that donate protons and bases are substances which accept these protons. It is pretty tricky because, if you look at water, it is both an acid and a base. If a water molecule is first a base, it accepts a proton from another water molecule, so that the water molecule that was first a base suddenly becomes an acid. It is quite difficult to keep up with that how it turns around.

…

(I) How would you write an acid-base reaction?

(S_7) Oh… Let's see, HCl is an acid and NaOH is a base. Then the result should be $HCl + NaOH \rightarrow NaH_2O + Cl^-$. HCl is the acid and NaOH is the base.

(I) What do you think when you write this equation?

(S_7) I think that a proton is transferred from the acid to the base.

…

(I) MC1 (NaOH + HCl) which one would you choose?

(S_7) I would choose this one: ($Na^+ + OH^- + H^+ + Cl^- \rightarrow NaCl + H_2O$). It shows clearly that OH^- and H^+ come together forming one molecule of water.

…

(I) Let's say that this is an acid-base reaction (MC1) just like this one ($HCl + NaOH \rightarrow NaH_2O + Cl^-$). You told me that HCl was the acid and that it donated a proton to the base, NaOH. Can you explain MC1 for me the same way?

(S_7) Yes, it is not exactly the same. No, it would be… we had two finished molecules

the whole time, which split up and came together. Here... It does not seem like an acid-base reaction. In that case they would split up more.

(I) They would split up more?

(S_7) Or, no yes, oh...I miss a proton all the time. Why did it not end up like this up here ($HCl + NaOH \rightarrow NaH_2O + Cl^-$)? It is exactly the same reaction.

(I) Yes, it is the same question, HCl + NaOH.

(S_7) Hmm... I don't know. Perhaps it strives to turn into water. If these two (Na^+ and Cl^-) are attracted more to each other and NaCl is a salt, right? Perhaps it has something to do with a metal and a non-metal attraction. They want to form a salt. And if OH and H have a stronger attraction to each other, I do not know.

(I) But this is not the way you reasoned before with the equation $HCl + NaOH \rightarrow NaH_2O + Cl^-$.

(S_7) No.

(I) Then there is a conflict here, about which you...

(S_7) Then, I believe more in this one (MC1). The metal and the non-metal attract each other and then OH and H will also attract each other.

General Discussion of the Results

The Areas of the Chemistry Curriculum the Students Liked and Disliked

Students disliked difficult areas of the chemistry curriculum that were too abstract or unstructured. They favoured intellectually fascinating parts that could be related to everyday life (to phenomena).This is in line with what students said in relation to acids and bases. Four students disliked the acid-base part of the curriculum. All of them were familiar with what was taught on the phenomenological level in this area, i.e., as long as it was based on the Arrhenius model and described using formula equations. They could, however, not interpret acid-base reactions properly on an abstract level according to Brønsted's model. It was also found in another study (Drechsler & Schmidt, 2005) that Swedish chemistry textbooks and the chemistry teachers interviewed did not differentiate between the different models used to describe acid-base reactions. Neither did students from the present study differentiate between the Brønsted and older models. For them, the acid-base chemistry seemed to be rather abstract. However, they may have wanted to understand that part of the chemistry curriculum too. Students said that in the area of acid-base chemistry, they missed clear explanations.

Students' Understanding of Acids and Bases

In Sweden, acid-base reactions are introduced at the phenomenological level at lower secondary school (ages 14 to 16). Students from upper secondary school (ages 17 to 19) are supposed to use the Brønsted model (Drechsler & Schmidt, 2005). The present study showed that students from our sample were familiar with describing acids and bases on the phenomenological level. The following knowledge statements were used to classify statements made in the interviews:

(1.1) Acids and bases are substances.

(1.2) In an acid-base reaction, substances react with each other forming new substances.

(1.3) In an acid-base reaction, acids and bases consume each other.

(1.4) The formation of salt and water is a prerequisite for an acid-base reaction.

(1.5) An acid-base reaction always results in a neutral solution.

(1.6) An acid-base reaction is properly described using a formula equation.

Students had, however, difficulties to apply the following knowledge statements to describe acid-base reactions according to Brønsted.

(2.1) Acids and bases are particles.

(2.2) In an acid-base reaction, particles react with each other forming new particles.

(2.3) In an acid-base reaction, an acid reacts with a base forming a new acid and a new base.

(2.4) The formation of water and salt is not a prerequisite for an acid-base reaction.

(2.5) In an acid-base reaction, the acid transfers a proton to the base forming a new acid-base pair.

(2.6) An acid-base reaction is properly described using an ionic equation.

Students sometimes identified H^+ as the acid, another time HCl. They referred to OH^- -ions or to NaOH as a base (1.1/2.1). They said: "*It is difficult to think about water as sour*" (1.1/2.1) or "*You can't imagine drinking an acid, but you drink water*" (1.1/2.1). Students confused the concepts "sour" and "acid" as well as "basic" and "base"(1.1/2.2). When discussing the results of Item 1, they looked for substances among the reactants or products (1.2/1.4). They assumed that a reaction between an acid and a base would always result in a neutral solution: "*In an acid-base reaction the result is neutral...They consume each other*" (1.3/1.5). "*In an acid-base reaction it becomes neutral*" (1.5).. Students had also difficulties to understand the proton-transfer between particles. "*If a water molecule is first a base, it takes a proton from another water molecule, so that... (it) suddenly becomes an acid. It is quite difficult to keep up with that...*" (2.3/2.5). "*base + acid → base H + acid –H (acid minus H)... this is difficult* (2.3/2.5). "*...water is both an acid and a base. It makes me think of something neutral*" (1.1/2.1/2.3/2.5).

Research has already reported that upper secondary students have difficulties to use the Brønsted model when asked to explain acid-base properties (e.g., Demerouti et al., 2004). The same was observed in this study. When writing acid-base reactions, students preferred substances 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. In this study, students confused the concepts 'acid,' 'sour,' and 'acidic substance' as well as the concepts 'base,' 'basic,' and 'basic substance.' This might explain their reluctance to accept water as an acid or as a base. It might also explain why they have difficulties to see any differences between the two models. In conclusion, it can be said that although students were expected to have learnt Brønsted's acid-base model they had not developed a clear picture of it.

Students' Understanding of Models

Another study with teachers performed in the same area of Sweden showed that teachers were well aware of the importance of using models in their classes. However, they seemed to have difficulties to apply this view to acids and bases (Drechsler & Schmidt, 2005). Teachers claimed that at upper secondary level, they taught the Brønsted model but used in fact – without explaining it – former models simultaneously. These findings may help to explain the results of the present study. Students realized that chemists used models to understand and explain observations and to test hypotheses. However, they did not connect this view to acids and bases. They were familiar with the Arrhenius model, but were not aware that *several* models are available to describe acid-base reactions. Confronted with a formula and an ionic equation for the same reaction, several students assumed that both contained the same information

Generalizability

We expect other researchers to identify similar problems in the area of acid-base chemistry by interviewing upper secondary school students, at least in Sweden, but also in other countries. There are four reasons for it:

(1) The interview guide 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, their generalizability is also assumed.

(2) Top students were selected for the interviews. If these students had problems to understand the Brønsted model, this should even more apply to ordinary students. Of course, they could have other additional problems as identified in the present study.

(3) Some of the difficulties students had to understand acids and bases have already 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. Drechsler and Schmidt (2005) found that textbooks and teachers were not aware of the different models used to explain acids and bases.

(4) Drechsler and Schmidt (2005) found the same "weaknesses" in the strategy of teachers and textbooks to teach acids and bases. For Drechsler and Schmidt (2005), this indicates 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.

Implications for Teaching and Research

"*...modelling should be developed whenever students are taught about non-observable phenomena...*" (Harrison & Treagust, 1996, p. 531). "*...omission in the classroom of the heuristics, strategies and criteria that drive generation, evaluation and revision of models, is likely to contribute to chemical illiteracy*" (Erduran, 2001, p. 589). 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 and ionic equations has to be made as well.

More research is needed for a better understanding of the role of acid-base models in teaching and learning. It has not been investigated so far how acid-base reactions are actually taught in Swedish schools. We also do not know how Swedish students apply their general view of models to other concepts in chemistry. A study that will clarify whether the results of the present study are applicable to students in other countries is also needed.

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Appendix 1

Interview guide

- Introduction
  - o Presentation: About the interviewer and the research project
  - o Permission to use tape recorder
  - o Questions from interviewee regarding the interview procedure
- Briefing
  - o Do you like school chemistry? Future plans?
  - o What do you remember from the chemistry course?
    - * Why do you remember this?
    - * Do you think the book was clear in this chapter?
  - o Were there chapters you did not like?
    - * Why did you dislike this chapter?
    - * Do you think the book was clear in this chapter?
- Main phase
  - o I would like to talk about acids and bases
    - * What do you remember about acids and bases?
      - Did you enjoy this chapter?
      - How did you study this chapter? (Book, lecture, discussion, laboratory work,...)
      - Did you learn many new things? Did you recognize the chapter from lower-secondary school?
      - Did you read a lot in the textbook?
  - o Do you remember acid-base reactions (Neutralization)?
    - * Can you write a reaction equation?
    - * What is the acid/base?
    - * What can you tell me about the products?
    - * Can you imagine another way to write this reaction? (e.g., a general equation)
  - o Multiple choice questions
    - * Solve task.
    - * Is this an acid-base reaction (proton transfer reaction)?
    - * What is the acid/base?
    - * What can you tell me about the products?
    - * Can you see any differences between the two reactions? Do you remember acid-base pairs?
  - o What is the corresponding acid/base to: NH_3/NaOH/CO_3^{2-}/$CaCO_3$)/H_3O^+/H_2O/OH^-
  - o Did you discuss the use of models in chemistry?
    - * What is a model to you?
    - * Are any of the following models to you: toy car, city map, reaction equation, periodic system of elements, the nitrogen cycle, a metaphor (e.g., Planets/atoms), balls stuck together with sticks, $Na^+(aq) + Cl^-(aq)$
      - Why? What is modelled?
      - Explain the term model to someone that is unfamiliar with models.
      - Why do chemists use models?
    - * Can you see the different way proton transfer reactions are written as different models?
- Debriefing
  - o I have no further questions. Questions from the interviewee, permission to use the recording, discuss some points of the interview.