

**Instructional Misconceptions in Acid–Base Equilibria:
An Analysis From a History and Philosophy of Science Perspective**

Abstract. The implications of history and philosophy of chemistry are explored in the context of chemical models. Models and modeling provide the context through which epistemological aspects of chemistry can be promoted. In this work, the development of ideas and models about acids and bases (with emphasis on the Arrhenius, the Brønsted-Lowry, and the Lewis models) are presented. In addition, misconceptions (alternative and instructional ones) on acid-base (ionic) equilibria are examined from the history and philosophy of science perspective. The relation between the development of the models and students' misconceptions are investigated. Finally, the hypothesis that history and philosophy could help educators anticipate students' misconceptions is examined.

Key words: *instructional misconceptions; acid-base chemistry; acid-base equilibria; ionic equilibria; history of chemistry; philosophy of chemistry; models for acids and bases*

1. Introduction

Students' concepts are a major area of science education research. Mental representations of concepts which is at variance with currently held scientific theory are termed *misconceptions* (Kesidou & Duit 1993; Lewis & Linn 1994), and are distinguished into two kinds: (a) *alternative* or *experiential* or *intuitive* or *native conceptions* and (b) *instructional misconceptions* (Skelly & Hall 1993; Nakiboglu 2003). In this paper, we use the term misconceptions without discriminating between alternative and instructional misconceptions.

In numerous areas of chemistry, misconceptions have been identified and in the literature there exist specific documented misconceptions. Acid-base chemistry has received some attention too. An important component of acid-base chemistry is the (ionic) equilibrium concept.

In a review of students' chemistry misconceptions, Griffiths (1994) identified fifteen misconceptions relating to acid and bases. Five of them are relevant to acid-base equilibria: 'more hydrogen gas is displaced from a strong acid because the strong acid contains more hydrogen bonds than a weak acid'; 'all acids are strong and powerful'; 'strong acids have a higher pH than do weak acids'; 'neutralization always results in a neutral solution'; 'because a salt contains neither hydrogen nor a hydroxyl group, its solution cannot contain hydronium nor hydroxide ions'. According to Schmidt (1991), the term 'neutralization' acts as a hidden persuader, leading to the misconception that the product of 'neutralization' is a neutral solution'.

In a similar review, Garnett, Garnett, and Hackling (1995) listed just five misconceptions. The first is identical to the first mentioned above, while the others are: 'a weak acid cannot perform as well as a strong acid'; and 'pH is a measure of acidity but not of basicity'. The authors refer specifically to the various models of acid-base behavior; thus, younger high-school students operate with the Arrhenius model, while older high-school and university students operate with both the Arrhenius and the Brønsted-Lowry models. Carr (1984) stated that the textbook treatment of these models is often confused, and this results in misconceptions with some students. Finally, in their review, Garnett et al. considered that clearly there is need for more work in this area, and predicted a number of areas and issues where misconceptions are likely: confusion between acid-base strength and concentration, the hydrolysis of salts, the selection and the role of indicators in acid-base titrations, the difference between equivalence and end points, and the amphoteric properties of some substances.

Following the above directive, we undertook to investigate further the misconceptions on the subject of acid-base equilibria among twelfth-grade Greek high school students (Demerouti 2002). In this work, we will treat part of our findings from the history and philosophy of science (HPS) perspective. It is pertinent at this point to mention that in a study on students' reasoning of incomplete chemical conversions and also of chemical equilibrium, Van Driel, De Vos, and Verloop (1998) emphasized the role of the historical development of these concepts. The study revealed similarities and differences between students' reasoning and that of 19th-century scientists. It is remarkable that most of the students reasoned in macroscopic terms, but only few related the observed phenomena to their corpuscular conceptions.

2. Rationale: The Role of History and Philosophy of Chemistry in Chemistry Education

Rodriguez and Niaz (2002) have shown that the importance of history and philosophy of science (HPS) has been recognized since the 1920s. "Chemist-historians" such as Kopp, Thomson, Berthelot, Ostwald, and Ihde have maintained a long tradition of interest in history of chemistry (Russell 1985). In the United States, suggestions for including the history of chemistry in chemistry teaching can be traced back to the 1930s (Jaffe 1938; Oppe 1936; Sammis 1932). In addition, history of science has captured the interest of some chemists and found a way into the curriculum (Akeroyd 1984; Ellis 1989; Herron 1997; Kauffman 1989). On the other hand, Brush (1978) has argued that the ahistorical nature of chemical education is a reflection of chemists' marginal interest in the historical dimension of their science.

Since the start of 1990s, there has also been an increasing interest in the examination of chemistry as a distinct branch of philosophy of science. An emergent group of philosophers of science have contributed to the formulation of philosophy of chemistry. However, according to Van Brakel (1994) and to Scerri and McIntyre (1997), the philosophical dimensions of chemistry have not received much attention.

Matthews (1998) has argued that philosophy is not far below the surface in any science classroom, as most textbooks and classroom discussions deal, among others, with law, theory, model, explanation, cause, hypothesis, confirmation, observation, evidence and idealization (p. 168). History and philosophy of chemistry have the potential to inform and guide chemistry education particularly through chemical epistemology (Erduran 2001), a line of inquiry that focuses on theories of chemical knowledge. Models and modeling provide a crucial and relevant context through which epistemological aspects of chemistry can be promoted.

This article attempts to present the development of the acid-base models, and to investigate the role of history and philosophy in anticipation of students' misconceptions in acid-base equilibria. According to Niaz and Rodriguez (2001) history and philosophy are already inside chemistry, so we do not have to wait or ask for its inclusion in the curriculum. It is necessary, however, to treat history and philosophy properly if we want our students to have conceptual understanding of scientific progress and practice.

2.1. THE EMERGENCE OF THE PHILOSOPHY OF CHEMISTRY

Since the start of the 1990s, a new branch of philosophy of science has begun to flourish (Scerri & McIntyre 1997; Brushan & Rosenfeld 2000; Van Brakel 2000). This is the philosophy of chemistry, a field which was at the forefront of scientific research before the turn of the twentieth century, but which seems to have been largely eclipsed, as chemistry came increasingly under the reductive spell of theoretical physics and quantum mechanics (Scerri 2001). The growth of the philosophy of chemistry has been placed in the context of the growth of the broader field of philosophy of science.

Some of the central questions in philosophy of science such as the distinctive features of science that set it apart from other endeavors have been traditionally addressed in terms of what is considered to be the paradigm science: physics. Even though the emphasis on the logical analysis of scientific theories has been challenged by philosophers, such as Popper, Kuhn, Feyerabend, Lakatos, and others more recent philosophers, the legacy of logical positivism as 'physics' dominating in philosophical analysis persists even today (Scerri & McIntyre 1997; Erduran 2001). Reduction of one science to another was argued on the basis of correspondence and derivation of laws across these sciences (Nagel 1961; Nye 1993). The assumption that chemistry is a reduced to physics science has prevailed within the mindset of the HPS community (e.g. Wasserman & Schaefer 1986).

Scerri (1991) argues that chemistry differs from physics generally not in terms of issues of predictions but in terms of classification. Whereas predictions in physics are based on mathematical models, chemical models rely more on qualitative aspects of matter. Chemistry has traditionally been concerned with qualities such as color, taste, smell. Although both physics and chemistry involve quantitative and dynamic concepts, such concepts are often accompanied by qualitative and classificatory concepts in chemistry, as is also typical in biology. Furthermore, class concepts are used in chemistry as a means of representation. Some examples are 'element', 'salt', 'acid' and 'base'. These class concepts help chemists in the investigation and classification of new substances, just as biology is concerned with classification of organisms. Unlike in chemistry and biology, in physics the tendency is towards mathematization, not classification of physics phenomena. Such differences that set apart chemistry from physics as a distinct domain of scientific inquiry have been overlooked within the reductionism framework.

Chemists would argue that although some chemical laws relate to physical laws, certain aspects of chemical principles do not necessarily reduce to physical principles. A nice example of this argument is the periodic table (Scerri 1994). Given that philosophy of chemistry is an emerging field, it is not surprising that the literature has barely addressed the applications of this field to chemistry education (Erduran 2000; Scerri 2000). Models and modeling, for instance, provide a crucial context through which philosophy of chemistry can be promoted in the classroom. The concepts of acid and base (classification models) are a good example that shows the difference between chemistry and physics, but they are also progressive models as atomic models are in physics and chemistry.

2.2. THE ROLE OF MODELS IN CHEMICAL EDUCATION

Chemists have often drawn attention to the significance of model and modeling in chemistry (Suckling, Suckling, and Suckling 1978; Tomasi 1988; Trindle 1984). For example in chemical kinetics, the mechanism of chemical change has been explained by various models throughout history of chemistry (Justi and Gilbert 1999): The 'anthropomorphic' model described a chemical change in terms of the readiness of the components to interact with each other. The 'affinity corpuscular' model emphasized chemical change in terms of atomic affinities. The 'first quantitative' model introduced the notion of proportionality of reactants for chemical change to occur (Erduran 2001). Then the 'mechanism' model began to outline steps in chemical reaction, while the 'thermodynamics' model introduced the role of molecular collision with sufficient energy.

Models are tentative schemes or structures that correspond to real objects, events, or classes of events, and that have explanatory power (National Research Council 1996 p. 117). In the case of acid-base chemistry, physical and chemical properties are explained with the models of Arrhenius, of Brønsted and Lowry, and of Lewis.

Students use models from an early age, but we are not sure that they understand them. Acquisition of declarative knowledge or conceptual information on models is only one aspect of learning models. Students need also to gain an appreciation of how and why these models are constructed. How have these been conventionally used in the chemistry classroom? The chemical models have been presented to students rather as final versions than as tentative representations (Grosslight, Unger, Jay, & Smith 1991; Weck 1995). Within the traditional framework of teaching, strategies and arguments underlying the development, evaluation and revision of chemical models are overlooked. Furthermore, textbooks and chemists often do not make clear distinctions between chemical models, but rather frequently present 'hybrid

models'. Chemists model the physical and chemical properties of matter in an effort to explain why matter behaves in certain ways. Note that mostly chemical models have been synonymous with ball-and-stick models used as visual aids (Grosslight et al 1991; Leisten 1994). However, the focus on chemical models as physical models underestimates the diversity and complexity of models in chemistry.

3. An Overview of the Development of Acid-and-Base Models

3.1. THE FIRST EMPIRICAL EFFORTS

The concepts of acid and base were already known during the years of the Greek period as is copied in Greek manuscripts (Ihde 1984, p. 12). Knowledge of acids during the Greek and Arabic periods was limited to vinegar, fruit, juices and hydrolysed salts. On the other hand, the term 'base' was used in the melanosis procedure. Early in the 1200s, the strong mineral acids sulphuric acid and aqua regia were first isolated (Hankins 1989).

The acid-alkali theory was a dualistic theory based upon the old Embedoclean idea of the war of opposites. We can assume that it stemmed directly from Helmont's work, who has explained digestion chemically as a fermentation process involving an acid under the control of a Paracelsian 'archeus' or internal alchemist (Block 1992, p. 53). Sylvius, one of his disciples and professor of medicine, believed that digestion was a warfare, followed by neutralization between acids and alkalis (Boas, 1956). Block mentions (1992, p. 53) that Tachenius, in the *Hippocrates chemists (1666)*, was concerned that the greatest need in 1600s was for a unifying theory of chemical classification and explanation to replace the tarnished hypothesis of the four elements. Tachenius argued instead that the properties and the behavior of substances lay in their acidity or alkalinity. The fundamental problem with Tachenius' suggestion was that there was no satisfactory definition of an acid and an alkali beyond a circular one that an acid effervesced with an alkali and vice versa.

In 1675, in '*Reflections upon the Hypothesis of Alkali and Acidium*', Boyle criticized Sylvius and Tachenius's theory (Block, 1992, p.61). He was able to object to the vagueness of the terms 'acid' and 'base' as commonly used in the theory. He pointed out that effervescence was not a good test of acidity since it was also a test for alkalinity. This also caused problems with metals: were metals acids or bases? Boyle made an important contribution to acid-base chemistry with the development of indicators. He found that a blue vegetable substance, syrup of violets, turned red with acids and green with alkalis, thus offering an experimentally based classification of acidic, alkaline and neutral solutions.

Antoine Lavoisier's basic idea was that acidity was caused by the presence of oxygen in the compound. This idea turned out to be wrong, but it is historically important since it is the first systematic attempt to chemically characterize acids and bases. At this time in scientific history, it was a common belief that the properties of acids could be traced back to a single substance.

After Davy and Dulong formulated their concept that hydrogen somehow was of significance in acids but oxygen was not essential, there was little further advancement in the understanding of acids until the studies of 'polybasic' acids made by Graham and Liebig in the 1830's (Ihde 1984, p. 199-201). Davy concluded that hydrochloric acid is a compound of chlorine and hydrogen. Liebig resurrected the ideas of Davy on the role of hydrogen in acids, thus abandoning the attempt to retain Bergelius' dualism in favour of a unitary concept. Justus Liebig proposed that an acid was a hydrogen-containing substance in which the hydrogen could be replaced by a metal. This definition proved sufficient for over 50 years

until the advent of Svante Arrhenius. In fact, it is still compatible with modern definitions. Liebig had no corresponding theoretical definition for bases. They were still identified, in an empirical fashion, as substances which neutralized acids. However, no one could explain why they did so. Arrhenius would be the first person to offer a, more or less, correct explanation for acid-base neutralization.

3.2. THE CONTRIBUTION OF ARRHENIUS AND THE DEVELOPMENT OF THE THEORY OF ELECTROLYTIC DISSOCIATION

Arrhenius (1887) suggests that when an acid, base or salt is dissolved in water, it splits up, or dissociates, spontaneously into positively and negative ions. Arrhenius gave a hint of the theory in his 1884 doctoral thesis, but because of the severe objections raised against an ionic dissociation hypothesis by his colleagues and supervisors he chose to speak about active and inactive parts of a molecule rather than the ionized and unionized parts (Arrhenius 1912).

The nature of the evidence gathered by Arrhenius to support the idea of the electrolytic dissociation is reported by de Berg (2003). The fact that salt solutions conduct electricity was supportive of the existence of charged species, ions in solution. As the salt was diluted, the molar conductivity increased until a limiting value was reached. So Arrhenius proposed that a salt, AB, can exist both as undissociated molecules, AB, and in the form of ions A^+ and B^- , so that equilibrium ($AB \rightleftharpoons A^+ + B^-$) exists in any salt solution in water. Arrhenius gave an ionic interpretation to the electrical conductivity. The results of electrical conductivity, freezing point depression, osmotic pressure and vapour pressure lowering experiments support Arrhenius' hypothesis of electrolytic dissociation. Arrhenius studied Raoult' data on the effect of dissolved substances on the freezing point of water (Raoult 1882a,b, 1884), and came to believe that the different properties of freezing point depression and electrical conductivity of solutions were fundamentally dependent on similar phenomena, that is, the partial dissociation into ions in moderately dilute solutions. Arrhenius used the idea of ionic dissociation to explain the similar values for the heats of neutralization that hydrochloric or hydrobromic or nitric acids gave when mixed with sodium hydroxide. He proposed (Arrhenius, 1912) that each acid-base reaction was equivalent to the same ionic reaction $H^+ + OH^- \rightarrow H_2O$.

Serious objections were raised against the theory of electrolytic dissociation by Armstrong (1896, p. 78), Fitzgerald (1896), Herroun (1896, p. 152), and Pickering (1897, p. 223). The objections were classified by de Berg (2003) under the following categories: a) the existence of oppositely charged ions, b) the role of the solvent in the solution, c) the view that a solute in a dilute solution behaves like a gas.

The fundamental idea proposed by Arrhenius in 1887, that ionic compounds dissociated spontaneously into their ions, when dissolved in water, still holds today but some of the details have changed to accommodate anomalies such as the role of the solvent, through ion-solvent interactions and ion-ion interactions, that were ignored by Arrhenius. Thus the theory saw further development during the twentieth century.

3.3. THE BRØNSTED-LOWRY MODEL DEVELOPMENT

Arrhenius' theory of acids and bases, based upon the hydrogen and hydroxyl ions, explained acid and base phenomena in aqueous systems, although it failed to account for the dissociation of acids, compounds belonging to the covalent class. Many researches on non-aqueous solutions indicated instances of behavior similar to neutralization even though hydrogen ions were not present. So in liquid ammonia the reaction $NH_4Cl + NaNH_2 \rightarrow 2NH_3$

+ NaCl showed a typical neutralization curve during electrometric titration (Idhe 1984, p. 547).

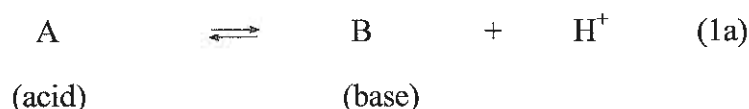
A completely enlarged viewpoint of acids and bases was developed from the proposals made in 1923 by Johannes Nicolaus Brønsted (in Denmark) and Thomas Martin Lowry (in England). These investigators proposed a definition based upon the role of hydrogen ion in acid-base systems. In his words (Brønsted 1923, p. 718)

"We have held steadily to the idea that compound A is an acid if it is partly or completely broken down in solution according to the scheme

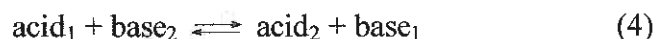


In scheme (1) in which the concept of an acid (A) is established, the concept of a base (B) is equally defined and thus the reciprocal connection of acidic and basic properties is shown in the clearest and simplest way.....

.....acids and bases are substances that are capable of splitting off or taking up hydrogen ions, respectively. The essence of this concept of defining acids and bases is once more given schematically by the expression:



The equilibrium formulated in scheme (1a) between hydrogen ion and the corresponding acid and base can be called a simple acid-base equilibrium. By mixing two simple systems, a double acid-base system and an acid-base equilibrium result that can always be formulated as follows:



So Brønsted introduced the idea of conjugated acid-base pair (scheme 1) as a reciprocal connection of acidic and basic properties. The equilibrium (4) includes a number of important reactions such as neutralization, hydrolysis, indicator reactions, etc. The reaction (4) might be expected to go in the direction favoring the formation of the weakest acid and base. According to this concept a neutralization reaction formed a new acid and base, not a solvent, the solvent itself figuring as an acid or base.

One important contribution coming from Lowry has to do with the state of the hydrogen ion in solution, for which Brønsted' used H^+ . Lowry, in his paper used the hydronium ion (H_3O^+) that is commonly used today. In Lowry's words (Lowry 1923, p.43-47):

"It is a remarkable fact that strong acidity is apparently developed only in mixtures and never in pure compounds. Even hydrogen chloride only becomes an acid when mixed with water. This can be explained by the extreme reluctance of a hydrogen nucleus to lead an isolated existence.... The effect of mixing hydrogen chloride with water is probably to provide an acceptor for the hydrogen nucleus so that the ionisation of the acid only involves the transfer of a proton from one octet to another."

So Brønsted and Lowry proposed a broader definition of acids and bases, independent of their behaviour in water us the acid and basic properties are independent of the nature of the solvent. The Brønsted-Lowry theory also provided a logical explanation for buffer action and common ion effect and revealed that a particular ion might act as an acid toward one reagent and as a base toward another. It thus broadened the scope of acid-base systems but was dependent on presence of hydrogen containing molecule or ion to serve as a proton

donor. The theory works very nicely in all protic solvents (water, ammonia, acetic acid, etc.), but fails to explain acid base behaviour in nonprotonated, where investigators could also see evidence of acid and base behaviour. That job is left for a more general theory, such as the Lewis theory.

3.4. THE LEWIS THEORY OF ACIDS AND BASES

G. N. Lewis suggested a scheme for handling acids and bases within a broader system in 1923 and developed it further in 1938. Sidgwick also contributed to the elaboration of the concept (Ihde 1984, p. 548). Lewis supported an acid to be any molecule or ion with an incomplete electron grouping around one of its atoms. This atom was able to accept an electron pair from another atom, the donor atom being present in an ion or molecule termed a 'Lewis base'. The concept of acids as electron pair acceptors made it possible to include such nonhydrogen containing molecules as SO_3 and SO_2 , consisting in a sense a return to the earlier day when the nonmetal oxide was considered an acid. Lewis (1938) argued:

'To restrict the group of acids to those substances which contain hydrogen interferes as seriously with the systematic understanding of chemistry as would the restriction of the term oxidizing to those substances containing oxygen'

What Lewis wanted, was a general definition of an acid and a base; one that was universal no matter what the chemical environment. The acid-base concepts have had a varied reception and illustrate the tentative nature of science. The hydrogen ion concept of acid is entirely adequate for aqueous systems, but the proton donor concept is necessary if liquid ammonia and acetic acid systems are to be considered. The electron pair acceptor concept of Lewis represents a still broader point of view which was useful in explaining certain reactions for which the other theories are inadequate.

Lewis also refocused the definition of acids and bases to something more fundamental about any atom: electrons. At the Cambridge symposium of 1923 Lewis he stated that "the electron has come and has come to stay and that chemists or physicists or more probably a team containing representatives of both groups must investigate the electronic structure of molecules" (Nye 1993, p. 276). In his theory, neither the hydrogen ion nor the solvent need be involved.

4. Students' Misconceptions on Acid-Base Equilibria

4.1. Method

A total of 119 students/university candidates, in their final high-school year (twelfth grade), participated in the study, during the 2001-2002 school year. In order to investigate the misconceptions in acid-base chemistry, and in particular in acid-base equilibria, a written questionnaire (in two forms A and B), each form consisting of ten multiple-choice and nine open-type questions, was constructed (Demerouti 2002). The questionnaire and the tests were given in seven schools in the greater Athens area, to students who had already been taught the chapter on ionic equilibrium. Because the Lewis model is not included in the curriculum, the questions only referred to the Arrhenius and the Brønsted-Lowry models.

The whole sample follows the normal distribution since, for the multiple-choice questions the skewness is -0.063 , and the kurtosis is -0.941 , while for the open type is 0.131 and -0.841 respectively. The reliability of the questionnaire was calculated by Cronbach alpha (α) coefficient, which assumed an average value of 0.63 for the multiple-choice type

questions, and of 0.78 for the open questions (form A: multiple choice 0.65, open questions 0.80; form B: multiple choice 0.61, open questions-0.75) .

In this paper, the possible relation between students' misconceptions and the way that textbooks and teaching style present models is examined. Results for both forms A and B of the multiple-choice questions 1, 2, 3, and 8, and the open questions 4, 5 and 6 are discussed (form A and form B). The reliability of a question can be judged by the value that *Cronbach's* α assumes if the item (the question) is deleted (Paraskevopoulos 1993). These values are 0.64, 0.60, 0.59, and 0.63 for the multiple choice questions 1, 2, 3, and 8 respectively, and these should be compared with the value 0.63 for the whole questionnaire. For the open questions 4, 5, and 6, the corresponding values are 0.76, 0.76, and 0.74 and these can be compared with the value 0.78 for the whole questionnaire. Finally, Table 1 reports discrimination indexes for the multiple-choice questions.

Table 1. Discrimination indexes for the multiple-choice questions.

Question	Form A	Form B
	D.I.	D.I.
1	0.57	0.40
2	0.50	0.33
3	0.89	0.51
8	0.46	0.45

4.2. FINDINGS

(NOTE: In multiple-choice questions, the correct option is shown in bold type)

4.2.1. Dissociation and Ionization

1A. Dissociation of a substance in water is the phenomenon where:

- a) ions are created during the dissolution of ionic compounds
- b) ions are created during the dissolution of molecular compounds
- c) **ions are released during the dissolution of ionic compounds**
- d) ions are released during the dissolution of molecular compounds

1B. Ionization of a substance in water is the phenomenon where:

- a) ions are created during the dissolution of ionic compounds
 - b) **ions are created during the dissolution of molecular compounds**
 - c) ions are released during the dissolution of ionic compounds
 - d) ions are released during the dissolution of molecular compounds
-

Table 2 has the results. 36.1% (in form A) and 53.5% (form B) of the students in question 1A can not distinguish the concepts dissociation and ionization. The percentage is higher for the ionization as it seems to be a more complex concept. Students use the two concepts with the same meaning. Molecular or ionic substances are dissociated or ionized during their dissolution in water. These results may also reflect the way that these concepts were developed, as Arrhenius used the concept 'dissociation' for both molecular and ionic substances. According to Arrhenius (1887) '...in order to explain electrical phenomena we must assume that some molecules of an electrolyte are dissociated...' The concept 'ionization' was clarified by Lewis. As Sevros mention, the efforts to explain the nature of

chemical bonds furnished a clearer understanding of the process of ionization. So the capacity of ionize was a property varied with the polarity of molecular bonds (Sevros 1996, p.135). Textbooks also employ these concepts as though they have the same meaning. In the words of the relevant Greek student text "...strong acids and strong bases are dissociated (or ionized)..." (Liodakis et al 2001).

Table 2. Students' answers (%) on question 1A and 1B.

Question	a	b	c	d	No answer
1A	11.5	8.2	60.6	16.4	3.3
1B	13.8	44.8	20.7	19	1.7

4.2.2. Definition of Brønsted-Lowry Acids and Bases

2A. Which of the following species is not a Brønsted-Lowry base? Justify your answer.

a) NH_3 , b) CN^- , c) H_2O , d) NH_4^+

2B. Which of the following species is not a Brønsted-Lowry acid? Justify your answer.

a) CH_3COOH , b) HCOO^- , c) H_2O , d) NH_4^+

As Table 3 shows, 83.6% of the students identified a 'none Brønsted-Lowry base' (2A), and 86.2% a 'none Brønsted-Lowry acid'. Most of the students seemed to identify substances as Brønsted-Lowry acids or bases. Table 4 shows that only 21.7% (form A) and 12.3% (form B) use the Brønsted-Lowry model to justify their choice. Most students seemed to be more familiar with the Arrhenius model. Many students used wrong explanations as they did not understand the Brønsted-Lowry model.

Table 3. Students' answers (%) on question 2A and 2B.

Question	a	b	c	d	No answer
2A	6.6	6.6	1.6	83.6	1.6
2B	1.7	86.2	6.9	3.5	1.7

Table 4. Students' justifications (%) on question 2A and 2B.

Question	Brønsted-Lowry	Arrhenius	No justification	Wrong
Form A	21.7	35.0	23.3	20.0
Form B	12.3	50.9	19.3	17.5

In the classroom and in the textbook the models have been presented to students rather as final versions than as tentative representations, so students did not understand why they have to use the one or the other model. The problem of Greek students is becoming more complicated, as they have to learn chemistry from a single textbook, which is the only source of knowledge for them and they have to memorize their textbook so they can get good grades which are essential for entrance to university. A part of those textbooks (Liodakis, 2001), which Greek students use at school, trying to explain models for acids and bases are still using hybrid models. For example when they describe the Arrhenius model, they also include the ionization of NH_3 which can be interpreted in terms of the Brønsted-Lowry model. Students obviously think that both models have the same conceptual context. Some researchers (Glynn, Britton, Semrud-Clikeman & Muth, 1989, Gilbert & Boulter, 1997) mention that textbooks often do not make clear distinctions between chemical models but

rather frequently present 'hybrid models'. Carr (1984) provides the following example which illustrates a common model confusion in textbooks:

Since NaOH is a strong base, Na^+ is an extremely weak conjugate acid; therefore, it has no tendency to react with H_2O to form NaOH and H^+ ion. (p.101)

The first statement is based on Arrhenius model of acids and bases. The second statement can be interpreted in terms of Brønsted-Lowry model although the emphasis on ionization is not consistent with this model (Carr, 1984). Also the need for including Brønsted-Lowry model in the textbook is justified by the fact that they have to learn more chemical neutralisation equations. When and why a new model is being used, and how this model differs from another model is not typically explained in textbooks and teaching.

3A. Which of the following species cannot act both as a Brønsted-Lowry base and a Brønsted-Lowry acid? Justify your answer.

a) HCO_3^- , b) HS^- , c) H_2O d) HCOO^-

3B. Which of the following species cannot act as an amphiprotic substance? Justify your answer.

a) HCOO^- , b) HCO_3^- , c) HS^- d) H_2O

Recall that Arrhenius classified a compound as an 'acid' if it contains hydrogen and releases hydrogen ions (H^+) and as a 'base' a compound that releases hydroxide ions in a solution, while the Brønsted-Lowry model illustrates this categorization as a competition between two substances for a proton. For example CH_3COOH is considered as acid in water, but also base in H_2SO_4 . If we present models as a 'rhetoric conclusion', e.g. 'acid is a proton donor', students cannot think that a substance may act both as an acid and as a base, depending on the environment. Table 5 has the results. We expected 3B to be the more difficult question for the students, but it seems that students of our sample made a new class, the amphoteric one. The results seem to support that a substance can be described as amphiprotic, but this does not have the meaning that it can act both as acid and base. An analysis of the students' justification is given in Table 6.

Table 5. Students' answers (%) on question 3A and 3B.

Question	a	b	c	d	No answer
3A	4.9	14.8	9.8	49.2	21.3
3B	70.7	3.5	10.3	5.2	10.3

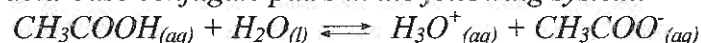
Table 6. Students' justifications (%) on question 3A and 3B.

Question	Brønsted-Lowry	Arrhenius	No justification	Wrong
Form A	10.4	29.2	31.2	29.2
Form B	5.8	38.5	28.8	26.9

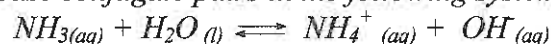
The analysis shows that the students were more familiar with the Arrhenius model, although in the final high-school year (twelfth grade) they were taught the Brønsted-Lowry model. The same result was obtained in the case of question 2, where the students did not identify why they had to use the one or the other model.

4.2.3. Definition of Conjugate Acid-Base Pair

4A. Identify all the acid-base conjugate pairs in the following system:



4B. Identify all the acid-base conjugate pairs in the following system:



Tables 7 and 8 have the results for questions 4A and 4B respectively. Most students (90.2% in the case of CH_3COOH , and 89.7% in the case of NH_3) identified only the conjugate acid-base pair that seems to be the predominant one: $\text{CH}_3\text{COOH} - \text{CH}_3\text{COO}^- / \text{NH}_4^+ - \text{NH}_3$. The percentage is lower for the conjugate pairs $\text{H}_3\text{O}^+ - \text{H}_2\text{O}$ and $\text{H}_2\text{O} - \text{OH}^-$. In the classroom and in the textbooks, often the same assumption is made, as they do not mention that the existence of an acid presupposes the existence of a base. Hydrogen chloride, for example, does not behave as an acid when it is dissolved in benzene because there are no molecules present that can accept protons. Similar results were obtained in question 5.

Table 7. Students' answers on question 4A.

4A	Conjugate acid-base	
	1*	2**
Mention	90.2%	77.0%
No mention	6.6%	9.8%
Opposite***	3.2%	13.1%

* relates to $\text{CH}_3\text{COOH} - \text{CH}_3\text{COO}^-$

** relates to $\text{H}_3\text{O}^+ - \text{H}_2\text{O}$

*** Opposite means students write base-acid

Table 8. Students' answers on question 4B.

4B	Conjugate acid-base	
	1*	2**
Mention	67.3%	89.7%
No mention	24.1%	8.6%
Opposite***	8.6%	1.7%

* relates to $\text{NH}_4^+ - \text{NH}_3$

** relates to $\text{H}_2\text{O} - \text{OH}^-$

*** Opposite means students write base-acid

4.2.4. Particles That Exist in an Aqueous Solutions / Systems in Ionic Equilibrium

5A. Write down all species (ions, molecules) that exist in a NH_4Cl aqueous solution.

As Table 9 shows, it seems to be difficult for a number of students to realize the existence of OH^- in an acidic solution. Also, many students failed to include the H_2O molecules. Only the particles with the largest concentration are more obvious.

Table 9. Students' answers on question 5B.

5B	NH_3	Cl^-	NH_4^+	OH^-	H_3O^+	H_2O
Mention	58.6%	86.2%	81%	39.7%	63.8%	39.7%

6B. Write down all the ionic equilibria that take place in a NH_4Cl aqueous solution. (NH_4Cl is soluble in water).

Similar results were obtained in the case of question 6B (Table 10): for most students, only the predominant equilibrium exists, that is, the one that is responsible for the acidic solution. In problem solving, as well as in textbooks (Liodakis, 2001) and in teaching, the equilibrium of water is not usually mentioned. This assumption creates misconceptions as those in questions 8A and 8B.

Table 10. Students' answers on question 6B

	Ionic equilibrium	
	1*	2**
Mention	63.8%	19.0%
No mention	24.1%	81.0%
Wrong	12.1%	-

*: $\text{NH}_4^+ + \text{H}_2\text{O} \rightleftharpoons \text{NH}_3 + \text{H}_3\text{O}^+$

** : $2\text{H}_2\text{O} \rightleftharpoons \text{H}_3\text{O}^+ + \text{OH}^-$

8A. What is (about) the pH value of a HCl 10^{-8}M aqueous solution? Explain.

a) 8, b) 7, c) Just over 7, d) Just under 7

8B. What is (about) the pH value of a NaOH 10^{-8}M aqueous solution? Explain.

a) Just over 7, b) Just under 7, c) 7, d) 8

Students' answers are shown in Table 11. Students usually learn that the strong acid determines the pH, so only the acid ionization (in this case: $\text{HCl} + \text{H}_2\text{O} \rightarrow \text{Cl}^- + \text{H}_3\text{O}^+$) is taken into account for determining the pH value. This strategy model using by teaching simplify the complexity of chemical systems, besides this model is not valid in all conditions. In the case of low acid concentration, the ionization equilibrium of water ($2\text{H}_2\text{O} \rightleftharpoons \text{H}_3\text{O}^+ + \text{OH}^-$) is important and should be taken into account too. It might be preferable then that a systematic consideration of all ionizations and equilibria involved should be made in all cases.

Table 11. Students' answers on question 8A and 8B.

Question	a	b	c	d	No answer
8A	13	1	5	42	0
8B	31	15	2	9	1

5. Discussion and Conclusions

Researchers in science education maintain that conceptual change, hence the whole process of learning, has not only cognitive character but also a metacognitive and an emotional one (Duit 1994; Tyson et al 1997). The metacognitive dimension includes the understanding of the nature of science, thus the understanding of the nature of scientific methodology. Students present alternative ideas about concepts, theories, and models at the cognitive level. Students' concepts (misconceptions) reflect also their alternative concepts about the nature of science. Students consider that scientific knowledge is the 'absolute truth' (Seroglou & Koumaras, 2001).

This brief survey of acid-base models and equilibria illustrates that certain criteria, such as behaviour of acids and bases independent of water, shaped the evaluation and revision of each model. The evolution of acid-base models illustrates an important epoch in the history of chemistry, the late 19th, when the nature of chemistry itself began to change, but also shows the progressiveness of chemical models, thus the tentative nature of science. Students' concepts on Arrhenius and Brønsted-Lowry models seem to be similar with the scientific ideas in the historical development of our conceptions of acids and bases.

Some researchers (Wandersee 1985; Benseguir 1989) have indicated history of science as a source of fruitful information that may help and prepare teachers to expect students' misconceptions. In the history of science, in those cases where scientists present contrasting arguments and theories then in the same content area students' misconceptions should be anticipated (Wiser & Carey 1983; Arons 1990; Sequeira & Leite, 1991; Whiteley 1993, Seroglou & Koumaras 2001). An argument for the inclusion of history and philosophy in chemistry instruction has been also based on the need to motivate student learning (Bent 1977; Brush 1978; Heeren 1990).

The importance of textbooks in science education has been recognized in transmitting to the students how a particular science has developed (Brush 1978; Jensen 1978, Kuhn 1970; McComas et al. 1998; Siegel 1978; Shiland 1998; Stinner 1992). Niaz and Rodriguez (2001) mentioned that most teachers in different parts of the world rely quite heavily on the textbook, as perhaps the only source of information. On the other hand, Niaz and Rodriguez (2000) have shown that most of the new and old textbooks not only ignore history and philosophy of science (HPS) but also present experimental findings as 'rhetoric of conclusions'. But such presentations are not conducive towards a better understanding of scientific progress. Siegel (1978), talking about textbooks, has emphasized the use of history and philosophy of science if we want textbooks not to be "... regarded as tools for inculcating in science students the principles and methods of the paradigm of today. Rather, textbooks are to function as challengers to students" (p. 309). Some researchers may argue that such an approach leads to misconceptions. Thus, in contrast to Siegel, some educators, following Kuhn (1970), would prefer students to be immersed in current paradigms, eventually providing them with the background for a critical appraisal (Hodson 1988; Lincoln 1989). We consider that it is better to present current theories, but also their development and the problems that demand theory/model revision.

History and philosophy of science can be introduced in the classroom not necessarily through formal courses in the history of chemistry or comments and anecdotes, but rather by incorporating the 'heuristic principles' that guided the scientists to elaborate their theories (Niaz & Rodriguez, 2000). History and philosophy in classroom can be present by emphasizing the evolutionary nature of science and promote discussion on the traditional consideration that science presents an 'absolute truth' about the natural world. If teachers want to teach chemistry more effectively they should recognize the nature of their own science: chemistry. The more a chemical educator knows about the various dimensions of scientific and in particular chemical, explanation the more effectively he/she teaches chemistry. While it is essential for chemical educators to be familiar with the details of many chemical theories, models and laws, which they hope to teach, it is equally important that they become aware of what theories, models and laws are in general, but also how they vary among the basic sciences of physics, chemistry and biology. The case of acid-base models highlights the need for reconceptualizing teaching by embodying chemical epistemology. History and philosophy is already 'inside' chemistry and this perspective can facilitate students' understanding.

ACKNOWLEDGEMENTS: Dr M. Kousathana wants to express her gratitude to Prof. K. Skordoulis for the long and lively discussions which stimulated and support this work. We would like to thank Prof. Niaz for his suggestions for improving this work. Finally, we thank the three reviewers for their detailed and constructive comments, which have contributed to the substantial improvement of our manuscript.

References

- Akeroyd, F.M.: 1984, 'Chemistry and the Popperism', *Journal of Chemical Education*, **61**(8), 697-698.
- Armstrong, H.E.: 1896, 'Letters to the Editor', *Nature* **55**(1413), 78.
- Arons, A.B.: 1990, *A Guide to Introductory Physics Teaching*, John Wiley, New York.
- Arrhenius, S.: 1887, 'Über die Dissociation der in Wasser gelösten Stoffe', *Zeitschrift für Physicalische Chemie* **i**, 631-648.
- Arrhenius, S.: 1912, 'Electrolytic Dissociation', *Journal of the American Chemical Society* **xxxiv**, 353-364.
- Benseghir, A.: 1989, *Transition Electrostatique – Electrocinétique: Point de Vue Historique et Analyse des Difficultés des Éléves*, Ph.D. Thesis, Université Paris VII.
- Bent, H.A.: 1977, 'Uses of History and Philosophy in Teaching Chemistry', *Journal of Chemical Education*, **54**, 462-466.
- Block, W. H.: 1992, *The Fontana history of chemistry*, Fontana Press, London, p. 53, 61.
- Boas, M.: 1956, 'Achévés internationale de histoire des Sciences', **9**, 13-28.
- Brønsted, J. N.: 1923, 'Some Remarks on the Concept of Acids and Bases', *Recueil des Travaux Chimiques des Pays-Bas*, **42**, 718-728.
- Brush, S.: 1978, 'Why Chemistry Needs History and How It Can Get Some', *Journal of College Science Teaching*, **7**, 288-291.
- Brushan, N. & Rosenfeld, S., eds: 2000, *Of Minds and Molecules*. Oxford University Press, New York.
- Carr, M.: 1984, 'Model Confusion in Chemistry', *Research in Science Education*, **14**, 97-103.
- de Berg K.C.: 2003, 'The development of the theory of electrolytic dissociation', *Science & Education*, **12**, 397-419.
- Demerouti M.: 2002, 'Misconceptions among Greek High School Students on the Subject of Ionic Equilibria' (in Greek), Thesis for graduate diploma in Chemistry Education and New Educational Technologies (DiCheNET), University of Athens, Athens.
- Duit, R.: 1994, 'Conceptual Change Approaches in Science Education'. Paper presented at the Symposium on Conceptual Change, Friedrich-Schiller-University of Jena, Germany. September 1-3, 1994.
- Ellis, P.: 1989, 'Practical Chemistry in a Historical Context', in M. Shortland & A. Warwick (eds), *Teaching the History of Science*, Basil Blackwell, Oxford.
- Erduran, S.: 2000, 'Emergence and Application of Philosophy of Chemistry in Chemistry Education', *School Science Review*, **81** (297), 85-87.
- Erduran, S.: 2000, 'A Missing Component in the Curriculum?', *Education in Chemistry*, **37**(6), 168.
- Erduran, S.: 2001, 'Philosophy of Chemistry: An Emerging Field with Implications for Chemistry Education', *Science & Education*, **10**, p. 581-593.
- Fitzgerald, G.F.: 1896, 'Helmholtz Memorial Lecture', *Journal of the Chemical Society* **LXIX**, 885-912.
- Hankins, T.L.: 1989, *Science and the Enlightenment*, Cambridge University Press.

- Heeren, J.K.: 1990, 'Teaching Chemistry by the Socratic Method', *Journal of Chemical Education*, **67** (4), 330-331.
- Herron, J.D.: 1997, 'The Place of History in the Teaching of Chemistry', *Journal of Chemical Education*, **54**(1), 15-16.
- Herroun, E.F.: 1896, 'Letters to the Editor', *Nature* **55**(1416), 152.
- Hodson, D.: 1988, 'Towards a Philosophically More Valid Science Curriculum', *Science Education*, **72**, 19-40.
- Idhle, A. J.: 1984, *The development of modern Chemistry*, Dover publications inc., p. 12, 199-201, 547-548.
- Jaffe, B.: 1938, 'The History of Chemistry and its Place in the Teaching of Chemistry', *Journal of Chemical Education*, **15**, 383-389.
- Jensen, W. B.; 1978, 'Logic, History, and the Chemistry Textbook', *Journal of Chemical Education*, **75**, 817-828.
- Justi, R. & Gilbert, J.: 1999, 'A Cause on Ahistorical Science Teaching: Use of Hybrid Models', *Science Education*, **83**(2), 163-167.
- Garnett, P.J., Garnett, P.J., & Hackling, M.W.: 1995, 'Students' Alternative Misconceptions in Chemistry: A Review of Research and Implications for Teaching and Learning', *Studies in Science Education*, **25**, 69-95.
- Gilbert, J. & Boulter, C.: 1997, 'Learning Science Through Models and Modeling' in B. Frazer & K. Tobin (eds), *The International Handbook of Science Education*, Kluwer Academic Publishers, Dordrecht.
- Glynn, S., Britton, B.K., Semrud-Clikeman, M. & Muth, K.D.: 1989, 'Analogical Reasoning and Problem Solving in Science Textbooks', in J.A. Glover, R.R. Ronning & C.R. Reynolds (eds), *Handbook in Creativity*, Plenum Press, New York, p. 383-398.
- Griffiths, A. K., 1994, 'A Critical Analysis and Synthesis of Research on Students' Chemistry Misconceptions' in H.J. Schmidt (Ed.), *Problem solving and misconceptions in chemistry and physics*, ICASE, pp. 70-79.
- Grosslight, K., Unger, C., Jay, E., & Smith, C.: 1991, 'Understanding Models and their Use in Science: Conceptions of Middle and High School Students Experts', *Journal of Research in Science Teaching*, **29**, 799-822.
- Kauffman, G.B.: 1989, 'History in the Chemistry Curriculum', *Interchange*, **20**(2), 163-177.
- Kesidou, S. & Duit, R.: 1993, 'Students' Conceptions of the Second Law of Thermodynamics - An Interpretive Study', *Journal of Research in Science Teaching*, **30**, 85-106.
- Kuhn, T.: 1970, *The structure of Scientific Revolutions* (2nd ed.), University of Chicago press, Chicago.
- Leisten, J.: 1994, 'Teaching Alchemy?', *Chemistry in Britain*, **30**(7), 552.
- Lewis, E. L. & Linn, M. C.: 1994, 'Heat Energy and Temperature Concepts of Adolescents, Adults, and Experts: Implications for Curricular Improvements', *Journal of Research in Science Teaching*, **31**, 657-677.
- Lewis, G.N.: 1938, *Journal Franklin Inst.*, **226**, 297
- Lincoln, Y.: 1989, 'Trouble in te Hand: The Paradigm Revolution in the Academic Disciplines', In J. C. Smart (Ed.), *Higher education: Handbook of Theory and Research*, Vol. V, Agathon Press, New York, pp.57-133.
- Liodakis, S, et al.: 2001, *Chemistry for Tenth Grade* (in Greek), OEDB, Athens, p. 85.
- Lowry, T. M.: 1923, 'The Uniqueness of Hydrogen', *Chemistry and Industry*, **42**, 43-47.
- McComas, W. F., Almazroa, H., & Clough, M.P.: 1998, 'The Nature of Science I n Science Education: An Introduction', *Science and Education*, **7**, 511-532.

- Matthews, M. R.: 1998, 'In the Defense of Modest Goals when Teaching about the Nature of Science', *Journal of Research in Science Teaching*, **35**, 161-174.
- Nagel, E.: 1961, *The structure of Science*, Harcourt, New York.
- Nakiboglu, C.: 2004, 'Instructional Misconceptions of Turkish Prospective Chemistry Teachers about Atomic Orbitals and Hybridization', *Chemistry Education: Research and Practice*, **4**, 171-188. [<http://www.uoi.gr/cerp>]
- National Research Council: 1996, *National Science Educational Standards*, National Academy Press, Washington DC.
- Niaz, M. & Rodriguez, M.: 2000, 'Teaching Chemistry as a Rhetoric of Conclusions or Heuristic Principles – A History and Philosophy of Science Perspective', *Chemical Education: Research and Practice in Europe*, **1**, 315-322. [<http://www.uoi.gr/cerp>]
- Niaz, M. & Rodriguez, M.: 2001, 'Do we have to Introduce History and Philosophy of Science or is it already inside Chemistry?', *Chemical Education: Research and Practice in Europe*, **2**, p 159-164. [<http://www.uoi.gr/cerp>]
- Nye, M.G.: 1993, *From Chemical Philosophy to Theoretical Chemistry*, University of California Press, Berkeley.
- Oppe, G.: 1936, 'The Use of Chemical History in the High School', *Journal of Chemical Education*, **13**, 412-414.
- Paraskevopoulos, N.I.: 1993, *Methodology of scientific research* (Volume 1 & 2, in Greek), Self-Publication, Athens.
- Pickering, S.: 1897, 'Letters to editor', *Nature*, **55**, (1419), 223.
- Raoult, F.M.: 1882a, *Comptes Rendus* **94**, 1517.
- Raoult, F.M.: 1882b, *Comptes Rendus* **95**, 1881.
- Raoult, F.M.: 1884, *Annales de Chimie Physique* **2**(vi), 66.
- Rodriguez, M. A. & Niaz, M.: 2002, 'How in Spite of The Rhetoric, History of Chemistry has Been Ignored In Presenting Atomic Structure In Textbooks', *Science & Education*, **11**(5), 423-441.
- Russell, C., A.: 1985, *Recent Developments in the History of Chemistry*, Royal Society of Chemistry, Whitstable Litho, Kent.
- Sammis, J. H.: 1932, 'A Plan for Including Biographical Material into Science Courses', *Journal of Chemical Education*, **9**, 900-902.
- Scerri, E.: 1991, 'Chemistry Spectroscopy and the Question of Reduction', *Journal of Chemical Education*, **68**, 122-126.
- Scerri, E.: 1994a, 'Predictions of the Nature of the Hafnium from Chemistry, Bohr's Theory and Quantum Theory', *Annals of Science*, **51**, 137-150.
- Scerri, E.R. & McIntyre, L.: 1997, 'The Case of Philosophy of Chemistry'. *Syntheses*, **111**, 213-232.
- Scerri, E.R.: 2000, 'The Failure of Reduction and How to Resist the Disunity of Science in Chemical Education', *Science & Education*, **9**, 405-425.
- Scerri, E.: 2001, 'The New Philosophy of Chemistry and its Relevance to Chemical Education', *Chemical Education: Research and Practice in Europe*, **2**, 165-170. [<http://www.uoi.gr/cerp>]
- Schmidt, H.-J.: 1991, 'A Label as a Hidden Persuader: Chemists' Neutralization Concept', *International Journal of Science Education*, **13**, 459-471.
- Sequeira, M. & Leite, L.: 1991, 'Alternative Conceptions and History of Science in Physics Teacher Education', *Science Education* **75**(1), 45-56.
- Seroglou, F. & Koumaras, P.: 2001, 'The contribution of the History of Physics in Physics Education: A review', *Science & Education*, **10**, 153-172.

- Sevros, J.W. : 1996, *Physical Chemistry From Ostwald to Pauling*, Prenceton University Press, p. 135.
- Siegel, H.: 1978, 'Kuhn and Schwab on Science Texts and the Goals on Science Education', *Educational theory*, **28**, 302-309.
- Shiland, T. W.: 1998, 'The Atheoretical Nature of The National Science Education Standards', *Science Education*, **82**, 615-617.
- Skelly, K. M. & Hall, D.: 1993, 'The Development and Validation of a Categorization of Sources of Misconceptions in Chemistry'. Paper presented at the *Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics*, Ithaca.
- Suckling, C.J., Suckling, K.E., & Suckling, C.W.: 1978, *Chemistry Through Models*, Cambridge University Press, Cambridge.
- Stinner, A.: 1992, 'Science Textbooks and Science Teaching: From Logic to Evidence', *Science Education*, **76**, 1-16.
- Tomasi, J.: 1988, 'Models and Modeling in Theoretical Chemistry', *Journal of Molecular Structure, (Theochem)*, **48**, 273-292.
- Trindle, C.: 1984, 'The Hierarchy of Models in Chemistry', *Croatica Chemica Acta*, **57**, 1231.
- Tyson, L. M., Venville, G. J., Harrison, A. G. & Treagust, D. F. : 1997, 'A Multidimensional Framework for Interpreting Conceptual Change Events in the Classroom', *Science Education* **81**, 387-404.
- Van Brakel, J.: 1994, 'On the Neglect of Philosophy of Chemistry', *Paper presented at the First International Conference on Philosophy of Chemistry*, London.
- Van Brakel, J.: 2000, *The philosophy of chemistry*, Louvain: University of Louvain Press.
- Van Driel, J.H., De Vos, W., & Verloop, N.: 1998, 'Relating Students' Reasoning to the History of Science: The Case Of Chemical Equilibrium', *Research in Science Education*, **28**, 187-198.
- Wandersee, J. H.: 1985, 'Can the History of Science Help Educators Anticipate Students' Misconceptions?', *Journal of Research in Science Teaching* **23**(7), 581-597.
- Wasserman, E. & Schaefer, H. F.: 1986, 'Methylene Geometry', *Science*, 233.
- Weck, M.A.: 1995, 'Are Today's models Tomottow's Misconceptions?' *Proceedings of the Third International History and Philosophy and Science Teaching Conference*, Vol. 2, University of Minnesota, Minneapolis, pp. 1286-1294.
- Whiteley, P.: 1993, 'The History of Physics – Its Use in a Caribbean Physics Syllabus', *School Science Review* **75**, 123-127.
- Wiser, M. & Carey, S.: 1983, 'When Heat and Temperature Were One', in D. Gentner & A. L. Stevens (eds), *Mental Models*, Lawrence Erlbaum Associates Publishers, Hillsdale, NJ/London.