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Understanding the Relationship Among Arrhenius, Brønsted−Lowry, and Lewis Theories

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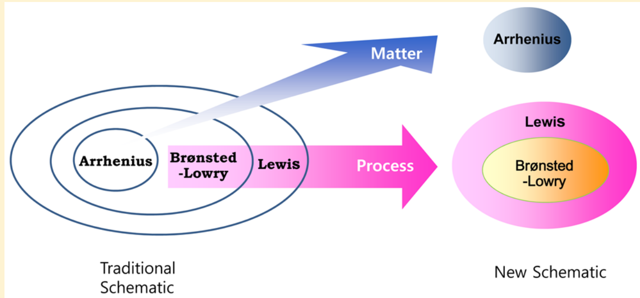
ABSTRACT: Many studies suggest that students have difficulties in learning acid-base concepts. This study presents some conflicts in the textbook descriptions of these concepts and proposes these to be the cause of the students' difficulties. This is especially true regarding the description of the relationship among the Arrhenius, Brønsted−Lowry, and Lewis concepts of acids and bases, which are represented schematically as a cumulatively developing figure. However, some reagents, such as NH_3, dry HCl, and H_2SO_4, cannot be classified as acid or base according to these descriptions. A new relationship is suggested in this study based on the ontological category of scientific knowledge. Finally, it is suggested that all three concepts be taught for the purpose of understanding not only the concepts but also the developmental nature of scientific theories.



KEYWORDS: *High-school/Introductory Chemistry, Misconceptions/Discrepant Events, Acids/Bases, First-Year Undergraduate/General, Curriculum, History/Philosophy, Textbooks/Reference Books, Lewis Acids/Bases*

INTRODUCTION

An understanding of acids and bases is an important part of the secondary school chemistry curriculum and also in general chemistry courses. However, many students have difficulty in learning acid−base concepts, as is shown in Table 1.

To solve this problem, several researchers have investigated the causes of these difficulties and suggested strategies to tackle them. Furió-Más et al.[1] proposed a systematic knowledge learning process to help students understand acid−base theories. Cokelez[4] suggested avoiding the term neutralization in teaching acid−base reactions and emphasized the need to aid the student's understanding through the organization of conceptual knowledge. Hawkes[9] and Logan[10] claimed that because the Brønsted−Lowry concept is a very simple one, the educational method that has traditionally taught the Arrhenius concept should be changed first. Luder[11] claimed that the development of the Lewis theory has been the result of a gradual broadening of the experimental foundation and that, therefore, only the Lewis theory should be taught.

However, some researchers[5,10,12] found the cause of the problem not to be the students but rather the textbooks themselves. Logan[10] claimed that the cause of this confusion comes from the way that textbooks are written. He suggested that scientific knowledge should not be presented as fact but that the assumptions made in formulating a theory should also be explained in the textbook. Briscoe[12] also stated that students should be able to distinguish between theory and fact and understand the proper place of scientific theories in textbooks.

In this study, I want to suggest another cause of the problem that arises from the descriptions used in textbooks. For this purpose, it is necessary to analyze the relationship between acid−base concepts in textbooks and in the related literature.

ANALYSIS OF THE RELATIONSHIP AMONG ACID−BASE CONCEPTS

Most general chemistry textbooks present the Arrhenius, Brønsted−Lowry, and Lewis concepts in the chapter on Acid and Bases. The relationship between the three concepts was described as linear and cumulative in the textbooks. Oxtoby et al.[13] expressed the Arrhenius, Brønsted−Lowry, and Lewis concepts as follows:

> *All these diverse reactions can be organized and discussed systematically by using generalized definitions of acids and bases, which include the Arrhenius definition as a limiting case.* ***We describe theses more general definitions as background for discussion acid−base equilibria for very broad classes of compounds.*** *The first of these models was proposed independently by Johannes Brønsted and Thomas Lowry in 1923, and the second was introduced by G. N. Lewis in the same year (p 671).*[13] *The Lewis model (Chapter 3), which focuses on the electron pair bond, provides a more general definitions of acid−base behavior, of which* ***the Arrhenius and Brønsted−Lowry definitions are special cases.*** *(p 674).*[13]

Similar definitions are expressed in other textbooks.[14−20] Indeed, some of the textbooks[21−23] present neither the Arrhenius nor Lewis concepts, yet in Atkins' book,[22] the Brønsted−Lowry concept was introduced as follows:

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Table 1. Literature Review of Students' Learning Difficulties with Acid–Base Concepts

Researcher	Subject	Type of Difficulties	Reason
Furió-Más et al.[1]	Grade 12 students (17–18 years old)	Students predicted acid or base only by looking at the existence of H^+ or OH^- in the formula of the substance.	Lack of knowledge and skills.
Won et al.[2]	College students	Students predicted acid or base only by looking at formula of the substance.	Lack of conjugated acid–base pair concepts.
Drechsler and Schmidt[3]	Upper secondary school Swedish students (17–19 years old)	List of misconceptions: Acids and bases are substances.	Students regard acid and base as forms of matter without paying attention to the motion of protons in learning the Brønsted–Lowry concept.
		In an acid–base reaction, acids and bases consume each other. The formation of salt and water is a prerequisite for an acid–base reaction.	
Cokelez[4]	Grade 11 Turkish and French students	An acid–base reaction produced a neutral solution, irrespective of the nature and quantities of the acids and bases.	Students are unable to recognize the scientific meaning of acid and base due to everyday life usage of these terms.
Furió-Más et al.[5]	Chemistry teachers and textbooks	Macroscopic and microscopic conceptual models of acid–base processes were mixed.	Lack of recognition that theories underwent paradigmatic changes.
		Linear and cumulative view in the construction of scientific knowledge	
Bretz and McClary[6]	Undergraduate organic chemistry students	Functional group determines acid strength. Stability determines acid strength.	Students consider conjugate base stability as the best reason to explain trends in acid strength
McClary and Talanquer[7]	Advanced college chemistry students	Acidity as an intrinsic property of substances.	Lack or very underdeveloped sense of mechanism for acid behavior. Acids are perceived as unstable substances.
		Acid strength determined by the presence of certain types of atoms or functional groups in the molecule.	
Stoyanovich et al.[8]	Undergraduate students	Confusion of acid–base definitions (e.g., mixing Arrhenius and Brønsted models or equating pH with acid–base strength)	Incorrect institution or incorrectly applied heuristic reasoning to solve acid–base chemistry from a single physical construct (i.e., bond polarization)
		Difficulty of providing examples of bases.	
		Difficulties applying simple acid–base concepts to biochemistry problems.	

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> *The Brønsted–Lowry theory focuses on the transfer of a proton from one species to another. However, the concepts of acids and bases have* ***a much wider significance*** *than the transfer of protons.* ***Even more substances can be classified*** *as acids or bases under the definitions developed by G. N. Lewis (p 426).*[22]

In these textbooks, the Brønsted–Lowry concept is portrayed as being more general than the Arrhenius concept, and the Lewis concept as more general still. Thus, overall, these concepts are believed to be progressing cumulatively. This is shown in Figure 1.

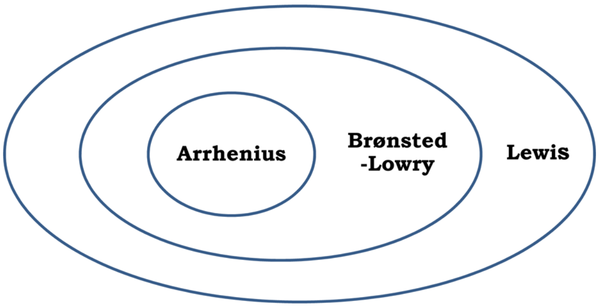

Figure 1. Traditional schematic of the relationship among Arrhenius, Brønsted–Lowry, and Lewis concepts.

The other textbooks studied discuss any one theory. For example, in "Chemistry" by Masterton et al., only the Arrhenius concept[24] is explained, Clayden et al. explains the Brønsted–Lowry concept[25] in "Organic Chemistry", and Louden's "Organic Chemistry" explains the Lewis concept.[26] In these textbooks, there is no attempt to explain the relationship between these concepts.

The relationship presented in Figure 1 is also represented in many articles on this subject. Along with the situation represented in Figure 2, Hall[27] stated, "As is the case in all actively growing sciences, the fundamental concepts of chemistry are not fixed, but change with the generations." Hall's opinion is thus aligned with those in review textbooks. Figure 2 is drawn in accordance with the reference.

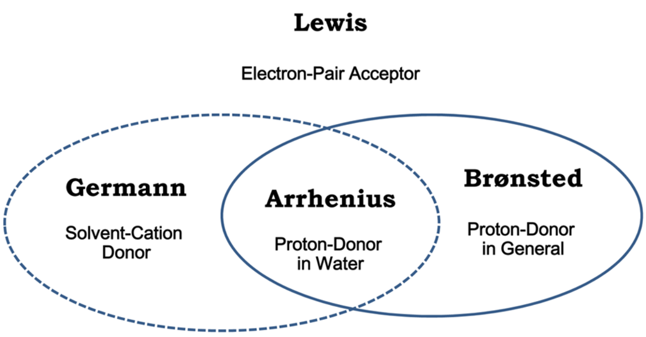

Figure 2. Hall's Diagram.

Similarly, Herron[28] stated that "Lewis' theory **broadens** the usual conception of an acid by calling any substance that was able to accept a co-ordinate share in an electron pair an acid." Moreover, Luder[11] suggested the viewpoint that concepts develop cumulatively in the statement, "The development of the Lewis theory has been the result of a gradual broadening of the experimental foundation." Jensen[29] also suggested a cumulatively developing figure comparing the three acid and base concepts. Figure 3 is drawn in accordance with the reference.

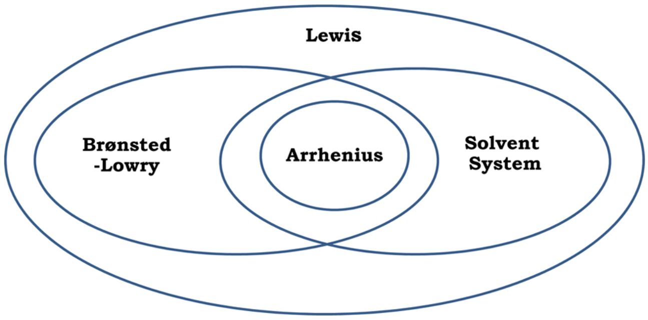

Figure 3. Jensen's Diagram.

In this linear and cumulative viewpoint, researchers claim that it is important to only teach the most sophisticated theory. For example, Hawkes[9] indicated that in traditional chemistry education, the Brønsted–Lowry concept is presented after the Arrhenius concept but that this kind of educational method causes students to have misconceptions; thus, the Brønsted–Lowry concept, which is simpler and clearer, should be introduced first. Shaffer[30] claimed that because all acid–base reactions can be explained with the Lewis concept, the other concepts should be unified and taught under the Lewis concept. This viewpoint is a kind of monism[31] that does not recognize the diversity of scientific concepts and theories. An awareness of the provisional nature of hypotheses and the assumptions made in formulating new concepts and theories should be presented to the students when teaching acid–base concepts.

Furió-Más el al.[1] investigated teachers' teaching of Arrhenius and Brønsted–Lowry concepts in American high schools and found the viewpoint of linear and cumulative development. They insisted that those teaching methods confused students because the students' understanding of the Brønsted–Lowry concept led them to believe that acid particles exist.

Briscoe[12] also mentions that the development of a new theory does not need the theory to be absolutely correct in order to occur. He insisted that when a scientific theory is explained, not only its original viewpoint and the conditions that adequately fit the theory but also its limitations must be presented.

From these, it can be determined that the studies of the viewpoint in which the three theories develop cumulatively fail to give clear explanations of the situational context of each concept.

In this study, differences in the description of NH_3, dry HCl, and H_2SO_4 by the different theories are examined.

■ CONFLICTS IN THE APPLICATION OF ACID–BASE CONCEPTS

Weak Base and Acid

Many textbooks[14,16,18,19] introduce NH_3 as a Brønsted–Lowry base in its reaction with H_2O, and indeed, it is the case that the Brønsted–Lowry description allows for a wider view of acids and bases than Arrhenius's.

Wilbraham et al.'s textbook introduces the reaction (p 443)[16]

$$NH_3 + H_2O \rightleftarrows NH_4^+ + OH^-$$

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The textbook explains that because NH_3 does not have an OH^- anion, it is not an Arrhenius base, but because it accepts a hydrogen ion, it is a Brønsted–Lowry base; in contrast, some textbooks[13,15] explain that because NH_3 can release an OH^- anion upon dissolving in water, it is an Arrhenius base.

Brown et al. provide the following explanation (p654)[15]:

> *Let us consider another example that compares the relationship between the Arrhenius and Brønsted–Lowry definitions of acids and bases; an aqueous solution of ammonia, in which we have the equilibrium:*
>
> $$\underset{\text{Base}}{NH_3(aq)} + \underset{\text{Acid}}{H_2O(l)} \rightleftharpoons NH_4^+(aq) + OH^-(aq)$$
>
> *Ammonia is a Brønsted–Lowry base because it accepts a proton from H_2O. Ammonia is also **<u>an Arrhenius base because adding it to water leads to an increase in the concentration of $OH^-(aq)$.</u>***

Such differences in viewpoints are caused by the conflicting preconditions of the Arrhenius concept, which assumes complete dissociation in aqueous solutions. In the Brønsted–Lowry concept, a base is not required to react with water.

The definitions of acids in the Arrhenius and Brønsted–Lowry concepts can be recognized as being the same, including the characteristic "substances that can donate protons". That is why the definition proposed by Brønsted–Lowry can be considered as an extension of that proposed by Arrhenius. However, this viewpoint is a mistake that occurs when the differences in the prerequisites of the two concepts are not recognized.

Creating a conflict with the Arrhenius concept by introducing the precondition of aqueous solutions is not an appropriate explanation for the Brønsted–Lowry concept, which has a different viewpoint than the Arrhenius concept.

For this reason, Zumdahl's textbook explains the Brønsted–Lowry concept using reactions in media other than aqueous solutions. Zumdahl's states (p642)[17]:

> *The Brønsted–Lowry model is not limited to aqueous solutions; it can be extended to reactions in the gas phase. For example, we discussed the reaction between gaseous hydrogen chloride and ammonia when we studied diffusion:*
>
> $$NH_3(g) + HCl(g) \rightleftarrows NH_4Cl(s)$$
>
> *In this reaction, a proton is donated by the hydrogen chloride to the ammonia, as shown by these Lewis structures: **<u>Note that this is not considered an acid–base reaction according to the Arrhenius concept.</u>***

The behavior of NH_3 in aqueous solutions may seem consistent with the Arrhenius concept. However, NH_3 is a weak acid; a reverse reaction can occur during the neutralization reaction, and conjugated acid and base are formed without water and salt products. This reaction cannot be explained by the Arrhenius concept.

If NH_3 is a base in the Brønsted–Lowry concept, it is because of its reaction with water. If it encountered solvents other than water, NH_3 would not have reacted as a base. The determination of an acid or base cannot be made on the basis of the material itself. However, some textbooks represent Brønsted–Lowry acids as materials. For example, in Prentice Hall's Textbooks,[32] "According to this theory, **<u>an acid is a substance</u>**, either molecule or ion, that can donate a proton to another substance."

The description of Brønsted–Lowry acid–base as a substance, or the creation of OH^- in aqueous solution, does not allow the students to expand their knowledge from that of the Arrhenius concept. It would be better to use H_3O^+ as the reactant, rather than H_2O, in its reaction with NH_3; Hall[33] expressed the reason why NH_3 is a base by following reaction 1.

$$H_3O^+ + NH_3 \rightleftarrows NH_4^+ + H_2O \qquad (1)$$

Through reaction 1, it can be shown more clearly that the reason why NH_3 is a base when it reacts with aqueous solutions is not because it releases OH^- but because it is a proton acceptor.

Weak acids and weak bases must also be dealt with in the Brønsted–Lowry concept. That is the reason for the representation of conjugate acid and base equilibria; meanwhile, Arrhenius reactions, which include strong acids and bases, represent only the forward direction (one-way arrow).

If students think that acids and bases are defined from the viewpoint of materials, the learner has difficulty in accepting the Brønsted–Lowry concept, wherein the same material can act as a proton donor or proton acceptor depending on the nature of the other material it encounters. Although OH^- is the strongest base in aqueous solutions, in other solvents, stronger bases (i.e., proton acceptors) can exist; hence, OH^- cannot always be called a base.[33] Therefore, a reaction process view is emphasized more in the Brønsted–Lowry concept.

According to the Brønsted–Lowry concept, even if the target material contains hydrogen, it will be difficult to immediately determine the material to be an acid because what material will be encountered is not predetermined. This kind of judgment is only possible during the course of a reaction after encountering another material. Therefore, unlike the Arrhenius concept, the Brønsted–Lowry concept discerns acid and base from the process and not the material itself.

Strong Acid

According to Arrhenius,[34] the concepts of acids and bases are defined within the context that they are strong electrolytes that completely dissociate in extremely dilute aqueous solutions. Arrhenius states that when an acid and a base encounter each other, neutralization occurs with the release of the heat of neutralization "that is true only for strong acids reacting with strong bases." He further added, "If I mix an absolutely active, that is, an extremely dilute, strong acid and a similar base in equivalent quantities, the same quantity of heat is always evolved and water is formed."

Many chemistry textbooks explain strong acids and bases using Arrhenius' definition; Oxtoby et al. explains strong acids as follows (p 676)[13]:

> *By the Arrhenius definition, HCl is the acid and NaOH is the base. By the Brønsted–Lowry definition, H_3O^+ is the acid and OH^- is the base. According to Lewis, H^+ is the acid and OH^- the base, because the proton accepts the lone pair donated by OH^- in the reaction.*

If the three concepts were viewed simply from a cumulative viewpoint, the Arrhenius, Brønsted–Lowry, and Lewis concepts would all view HCl as an acid. However, Oxtoby et al. viewed HCl only as an "Arrhenius acid", that is, an acid in the Arrhenius sense. Meanwhile, Chang[35] indicated that because HCl in a gaseous state (that is, not in aqueous solution) does not break down protons and react with NH_3, this should be explained by the Lewis concept.

Hall[33] indicated that completely dried liquids and gaseous nonmetal radical hydrates do not exhibit acidity, but because they have relatively high H^+ activities, they are clearly classified

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as acids under the Brønsted−Lowry concept. Broscoe[12] also said that HCl was an acid in the Brønsted−Lowry concept. These perspectives look at the Arrhenius concept and the Brønsted−Lowry concept as being the same.

The case of sulfuric acid has the same problem. Brown et al. stated that sulfuric acid is an Arrhenius acid because it is a proton donor and presented the following two reactions (p124)[15]:

$$H_2SO_4(aq) \rightarrow H^+(aq) + HSO_4^-(aq) \quad (2)$$

$$HSO_4^-(aq) \rightleftarrows H^+(aq) + SO_4^{2-}(aq) \quad (3)$$

However, although H_2SO_4 in reaction 2, which releases protons from complete dissociation in very diluted solutions, can be considered an Arrhenius acid, HSO_4^- in reaction 3 is not an Arrhenius acid. The differences can also be seen from the one-way arrow in reaction 2 and the two-way arrow in reaction 3. Therefore, Brown et al.'s explanation of Arrhenius acid as releasing protons by presenting the two reactions side by side is considered to be the same viewpoint as both Brønsted−Lowry and Arrhenius.

CONCLUSIONS AND IMPLICATIONS

Despite many studies pointing out students' confusions and suggesting the need for improvements, what is the reason that this problem has not been solved to date? Although a variety of responses are possible for this question, I suggest the cause of the problem is the basis of the textbook explanations.

Chi et al.[36] classified scientific concepts into two ontological categories: matter and process; however, during the learning process, it is very difficult for the learner to change ontological status from the prior concept to the proposed concept. From this point of view, it can be said that the Arrhenius theory, which views acids and bases as materials, and the Brønsted−Lowry theory, which views an acid or a base as a reaction process, demand a different ontological status from each other.

Chemistry is the study of matter and reaction. In this respect, it can be considered that the focus of the Arrhenius concept is matter and the focus of the Brønsted−Lowry and Lewis concepts is process. The Lewis concept is a definition that can be considered an extension of the Brønsted−Lowry concept in that it includes acidic or basic liquid form after neutralization and, in that the same matter, can be relatively acidic or basic depending on the reaction, both of which are included in the Brønsted−Lowry concept; however, it also includes reactions that do not involve various states or protons, which the Brønsted−Lowry concept does not include. Therefore, the Arrhenius concept and the Brønsted−Lowry concept (including the Lewis concept) belong to different categories. This is shown in Figure 4.

The viewpoint that the concepts are cumulative and the progressive development of a theory may confuse students. Chang[31] indicated that theoretical frameworks did not follow from one another in a cumulative-progressive way; the relationship between them is closer to incommensurability than reduction. This statement can be applied to Arrhenius, Brønsted−Lowry, and Lewis concepts. Paik et al.[37] suggested that preservice secondary science teachers had difficulties in learning the Arrhenius and Brønsted−Lowry concepts because they tried to understand it using the Arrhenius model. Once they recognized that the two concepts have different contexts, they understood the cause of their past learning difficulties and the tentative nature of scientific knowledge. The teachers suggested that nonsequential learning of the topic could be useful, as would more opportunities to compare the models.

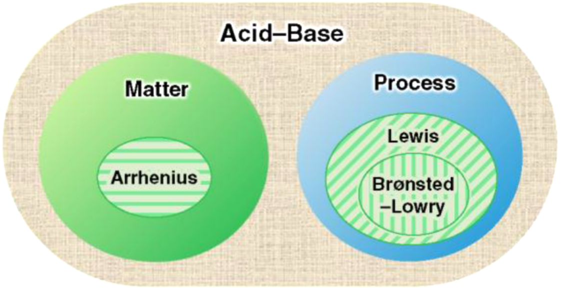

Figure 4. Relationship among Arrhenius, Brønsted−Lowry, and Lewis acid−base concepts.

The Arrhenius concept is still used widely for many acid and base reactions. Many chemical reactions occur in aqueous solutions because many compounds have hydrogen or hydroxide ions. It would not be prudent to discard a theory that is easy to understand and is well applicable in many cases.

Moreover, teaching the Arrhenius concept is important for the purpose of promoting recognition of the meaning of the concept or theory in science learning. However, for this purpose, introduction of newly presented concepts needs to follow in order to overcome the limitations of the Arrhenius concept.

LIMITATIONS OF THE STUDY

In this paper, I suggest the possibility that the difficulty students experience learning about acid−base concepts originates from discrepancies in the descriptions of acid−base concepts in textbooks. This correlates with a previous paper[35] that studied preservice secondary science teachers' responses about their own learning difficulties. That paper also noted the insight the teachers gained after learning about the different contexts of the different acid−base concepts. The principle limitation of this study is that stronger evidence for this hypothesis, sourced from student responses to the teaching suggestions, is required.

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Notes

The authors declare no competing financial interest.

REFERENCES

(1) Calatayud, M. L.; Barcenas, S. L.; Furió-Más, C. Surveying students' conceptual and procedural knowledge of acid-base behavior of substances. *J. Chem. Educ.* **2007**, *84* (10), 1717−1724.

(2) Won, J. A.; Gwak, J. R.; Park, Y. N.; Paik, S. H. A Research of Chemistry Education Major Pre-Service Teachers' Conceptions Related to Acid-Base - Neutralization Reaction. *Korean Journal of Teacher Education* **2010**, *26* (2), 65−87.

(3) Drechsler, M.; Schmidt, H. Upper secondary school students' understanding of models used in chemistry to define acids and bases. *Sci. Educ. Int.* **2005**, *16* (1), 39−53.

(4) Cokelez, A. A comparative study of French and Turkish students' ideas on acid-base reaction. *J. Chem. Educ.* **2010**, *87* (1), 102−106.

(5) Furió-Más, C.; Calatayud, M. L.; Guisasolac, J.; Furió-Gómeza, C. How are the Concepts and Theories of Acid−-Base Reactions Presented? Chemistry in Textbooks and as Presented by Teachers. *Int. J. Sci. Educ.* **2005**, *27* (11), 1337−1358.

DOI: 10.1021/ed500891w
J. Chem. Educ. 2015, 92, 1484−1489

(6) Bretz, S. L.; McClary, L. Students' Understandings of Acid Strength: How Meaningful is Reliability When Measuring Alternative Conceptions? *J. Chem. Educ.* **2015**, *92*, 212−219.
(7) McClary, L.; Talanquer, V. College Chemistry Students' Mental Models of Acids and Acid Strength. *J. Res. Sci. Teach.* **2011**, *48* (4), 396−413.
(8) Stoyanovich, C.; Gandhi, A.; Flynn, A. B. Acid-Base Learning Outcomes for Students in an Introductory Organic Chemistry Cours. *J. Chem. Educ.* **2015**, *92*, 220−229.
(9) Hawkes, S. J. Arrhenius confuses students. *J. Chem. Educ.* **1992**, *69* (7), 542−543.
(10) Logan, T. S. The presentation of acids and bases in textbooks. *J. Chem. Educ.* **1949**, *26*, 149−153.
(11) Luder, W. F. Contemporary acid-base theory. *J. Chem. Educ.* **1948**, *25*, 555−558.
(12) Briscoe, H. T. Teaching the new concepts of acids and bases in general chemistry. *J. Chem. Educ.* **1940**, *17*, 128−130.
(13) Oxtoby, D. W.; Gills, H. P.; Campion, A. *Principles of Modern Chemistry*, 7th ed.; Cengage Learning: Boston, 2011.
(14) McMurry, J. E.; Fay, R. C.; Fantini, J. *Chemistry*, 6th ed.; Pearson Education Inc.: Upper Saddle River, NJ, 2012.
(15) Brown, T. E.; LeMay, H. E. H.; Bursten, B. E.; Woodward, P.; Murphy, C. *Chemistry The Central Science*, 12th ed.; Prentice Hall: NY, 2011.
(16) Wilbraham, A. C.; Staley, D. D.; Simpson, C. J.; Matta, M. S. *Chemistry*, 2nd ed.; Addison-Wesley Publishing Company: Menlo Park, CA, 1990.
(17) Zumdahl, S. S.; Zumdahl, S. A. *Chemistry*, 8th ed.; Brooks/Cole, Cengage Learning: Belmont, CA, 2010.
(18) Silberberg, M. S. *Principles of General Chemistry*, 1st ed.; The McGraw-Hill Company: NY, 2008.
(19) Wade, L. G. *Organic chemistry*, 8th ed.; Pearson Education Inc.: Boston, MA, 2013.
(20) Kelter, P.; Mosher, M.; Scott, A. *Chemistry: The Practical Science*, 1st ed.; Houghton Mifflin Company: Boston, 2008.
(21) Suchocki, J. *Conceptual Chemistry*, 4th ed.; Pearson Education Inc.: NY, 2011.
(22) Atkins, P.; Jones, L. *Chemical Principles: The Quest For Insight*, 5th ed.; W.H. Freeman & Co Ltd: New York, 2012.
(23) The American Chemical Society. *General Chemistry*, 1st ed.; W.H. Freeman and Company: NY, 2005.
(24) Masterton, W. L.; Slowinski, E. J.; Walford, E. T. *Chemistry*; Holt, Rinehart and Winston: NY, 1980.
(25) Clayden, J.; Greeves, N.; Warren, P.; Wothers, S. *Organic Chemistry*; Oxford Univ. Press.: Oxford, UK, 2001.
(26) Louden, M. *Organic Chemistry*, 5th ed.; Roberts and Company Publishers: Englewood, CO, 2009.
(27) Hall, N. F. Modern conceptions of acids and bases. *J. Chem. Educ.* **1930**, *7* (4), 782−793.
(28) Herron, F. Y. Models illustrating the Lewis theory of acids and bases. *J. Chem. Educ.* **1953**, *30*, 199−201.
(29) Jensen, W. B. *The Lewis Acid-Base Concepts*; John Wiley and Sons, Inc.: New York, 1980; pp 65−67.
(30) Shaffer, A. A. Let us Give Lewis Acid-Base Theory the Priority it Deserves. *J. Chem. Educ.* **2006**, *83* (12), 1746−1749.
(31) Chang, H. S. *Is Water H_2O?*; Springer: London, 2012.
(32) Dorin, H.; Demmin, P. E.; Gabel, D. L. *Prentice Hall Chemistry: The study of matter*, 4th ed.; Prentice Hall: Needham, 1992.
(33) Hall, N. F. Systems of acids and bases. *J. Chem. Educ.* **1940**, *17*, 124−128.
(34) Arrhenius, S. Electrolytic dissociation. *J. Am. Chem. Soc.* **1912**, *34* (4), 353−364.
(35) Chang, H. Acidity: The persistence of the everyday in the scientific. *Philos. of Sci.* **2012**, *79* (5), 690−700.
(36) Chi, M. T. H.; Soltta, J. D.; de Leeuw, N. From things to processes: a theory of conceptual change for learning science conceptions. *Learn. Instr.* **1994**, *4*, 27−43.
(37) Paik, S. H.; Kang, N. H.; Sin, E. J. Korean Secondary Preservice Teachers' Understanding of Learning Difficulties in Acid and Base Models: Reflections through Nature of Science Lessons. Paper presented in 2014 Second IHPST Asian Regional Conference, Taipei, Taiwan.

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J. Chem. Educ. 2015, 92, 1484−1489