High school students' understanding of titrations and related acid-base phenomena

Keith Sheppard

Program in Science Education, Teachers College, Columbia University,
525 West 120th Street, New York, NY, 10027, USA
e-mail: sheppard@tc.columbia.edu

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Abstract: Acid-base titrations are common laboratory activities carried out in high school chemistry courses. Using a series of qualitative and computer-based tasks, this study examined sixteen American students' understanding of titrations. The findings indicated that students had considerable difficulty with acid-base chemistry, were unable to describe accurately acid-base concepts, such as pH, neutralization, strength, and the theoretical descriptions of acids and bases. Further, most students could not relate the concepts to actual solutions. Student difficulties stemmed from a lack of understanding of some underlying chemistry, such as the nature of chemical change and the particulate nature of matter. A number of factors were identified as contributing to these difficulties, including the overstuffed nature of introductory chemistry itself, the emphasis during instruction on solving numerical problems, and the dominant role played by the textbook. The conceptual density of acid-base chemistry, the confusing nature of acid-base terminology and the lack of agreement about what material should be included in the chemistry curriculum were identified as being problematic. [*Chem. Educ. Res. Pract.*, 2006, **7** (1), 32-45]

Keywords: Acid-base models, titration, pH, neutralization, student conceptions

Introduction

Acid-base titrations are common experiments carried out by students in introductory chemistry classes. The topic has been a regular component of introductory chemistry curricula for decades, and receives wide coverage in introductory texts and related laboratory manuals (Dorin, 1987; Wilbraham et al., 1996; Dingrando et al., 2002). The most frequently conducted titrations involve the neutralization of strong acids with strong bases, with students being required to calculate the concentration of unknowns using this method. Some introductory texts (Dingrando et al., 2002) extend the topic to include details of titration curves. *A framework for high school science education* (Aldridge, 1996) suggested that students in grade 11 should be able to use the pH scale to investigate changes in pH that occur during titrations. The treatment of titration curves in introductory chemistry classes is usually non-mathematical, and they are most often included as a means of determining the most appropriate indicators to use in particular titrations.

That students have difficulty learning chemistry has been well documented (Gabel and Bunce, 1994), and has been attributed to a variety of factors such as, the abstractness of the subject (Herron, 1975), the complexity of the calculations involved, the remoteness of the language used (Glassman, 1967) and the different representational levels that chemists use

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(Gabel, et al., 1987; Nakhleh and Kracjik, 1994). These difficulties carry into all areas of chemistry and an increasing number of studies have focused on student difficulties with the concepts of acid-base chemistry. The causes of student difficulties with acid-base chemistry have been ascribed to the existence of many alternative conceptions or misconceptions (Hand and Treagust, 1988; Hand, 1989; Schmidt, 1997; Sheppard, 1997; Demerouti et al., 2004; Demircioglu, 2005), a poor understanding of the particulate nature of matter (Nakhleh and Kracjik, 1993; Nakhleh, 1994; Smith and Metz, 1996), difficulties with the use of different models used in acid–base chemistry (Carr, 1984; Schmidt, 1995; Vidyapati and Seetharamappa, 1995; Sheppard, 1997; Furio-Mas et al., 2005; Kousathana, et al., 2005) and confusion between acid–base terminology and everyday words (Schmidt, 1991, 1995).

Some of the previous research has focused on particular acid-base concepts such as neutralization and pH. Cros et al. (1986, 1988) noted that college students tended to retain a descriptive definition of pH despite instruction that emphasized its more quantitative aspects. Ross and Munby (1991) noted that high school students demonstrated a good qualitative understanding of pH, while in contrast, Nakhleh (1990), in a more in-depth study, noted that high school students had relatively poor qualitative understanding of pH. Schmidt (1995) reported that students consider the products of neutralization reactions to always have a pH of 7 and he described neutralization as a ‘hidden persuader’. Given these reported issues, it seems likely that students will have difficulty with understanding what is happening to the values of pH during a titration. This study documents high school chemistry students’ attempts to explain what is happening during a titration and focuses on students’ understanding of several related acid-base concepts such as acid, base, neutralization, pH, along with the use of various acid-base models.

Method

Subjects

Sixteen students from three introductory high school chemistry classes were interviewed for the study. All students were either 16 or 17 years old and were in grades 10 or 11. The students attended a school in the North-Eastern United States, and followed their state chemistry curriculum. As is the common practice in the USA, introductory chemistry is taught as a single-year course usually in the 10^{th} or 11^{th} grade (Sheppard and Robbins, 2005). A small fraction of students complete a second year of chemistry, though such courses are invariably college level courses and involve a detailed mathematical treatment of acid-base equilibria. The students in this study had all successfully completed biology in the year before taking chemistry. They were taught by the same chemistry teacher, and received a traditional lecture-based instruction with a weekly double period of laboratory work. The introductory chemistry curriculum required students to be familiar with both the Arrhenius and Brønsted-Lowry acid-base models, though not the Lewis model, with examination questions being set that required students to distinguish between acids and bases from both perspectives. As part of their chemistry instruction the students had carried out two acid-base titrations while completing their unit on acids and bases.

Procedure

The study used a variety of qualitative research techniques to determine students’ understanding of acid-base ideas. In ‘interview about events’ techniques students are questioned about their understanding of events or phenomena using practical situations. Students are then questioned about the phenomena and are asked to explain it. The technique has been used

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extensively in science education research (Osborne and Cosgrove, 1983). The 'Prediction-Observation-Explanation' or POE technique, probes understanding using three separate, but related tasks (White and Gunstone, 1992). Given a situation or event, such as the effect of bases on indicators, students are asked first to predict the outcome of the event and to give an account for their reasoning. Next, they perform the task and make observations, before finally explaining the outcome and reconciling any differences between their predictions and the actual outcome of the event. The technique is particularly useful for eliciting students' ideas, and is used to measure their ability to apply knowledge. That students hold ideas about phenomena and use these ideas to determine what observations to make, highlights the theory dependent nature of POEs (Gunstone and Champagne, 1990). The POE technique has also been used successfully in a number of studies (see for example, Woods and Thorley, 1993) . The technique is straightforward and students often react positively, though it is important that students should commit themselves to a prediction before performing a task. Reconciling discrepancies between predictions and the outcome of the tasks can be difficult for many students (White and Gunstone, 1992). The third technique uses drawings, which allow students to show understanding that may be hidden from other procedures. For instance, students' drawings of solutions can reveal more information about their views on the particulate nature of matter, the role and nature of the solute and solvent than could be obtained from verbal or written data (Nakhleh, 1994). In the procedure, students are asked to draw what they see or think that they will see in a given event. The technique may be applied to macroscopic objects or to non-visible objects such as atoms and ions, where its use is particularly powerful. The technique has been used in a number of studies (Yarroch, 1985; Ben Zvi, et al., 1987; Lythcott, 1990; Nakhleh et al., 2005).

Table 1. Interview tasks.

Task	Activity	Purpose/Rationale
1. Introductory pH event	Students were shown beakers with colorless solutions marked 'pH 3','pH 5' and 'pH 11', and were asked to explain their sub-microscopic composition using drawings.	Elicit ideas about pH, concentration, strength, acid and base.
2. Neutralization	A small amount of acid was mixed with an equal amount of base, a) with no indicator present, b) with phenolphthalein indicator present.	Elicit ideas about acid-base reactions, neutralization and pH.
3. Questions about the models	Using the descriptions from the two previous tasks, students were asked to explain their understanding of pH and neutralization and the different acid-base models.	To determine which theoretical description the students utilized. To show how the various concepts were inter-related, and as a template for further questioning.
4. Acid-base titration	A titration was conducted using a pH electrode interfaced to a computer. Students were asked to predict and explain what would happen to the pH as the titration was conducted. After the titration, the students were asked to account for differences between their predictions and the outcome.	To determine students' ideas about pH, acid, base, neutralization, and to determine which theoretical perspective the students would use when explaining the titration curve.

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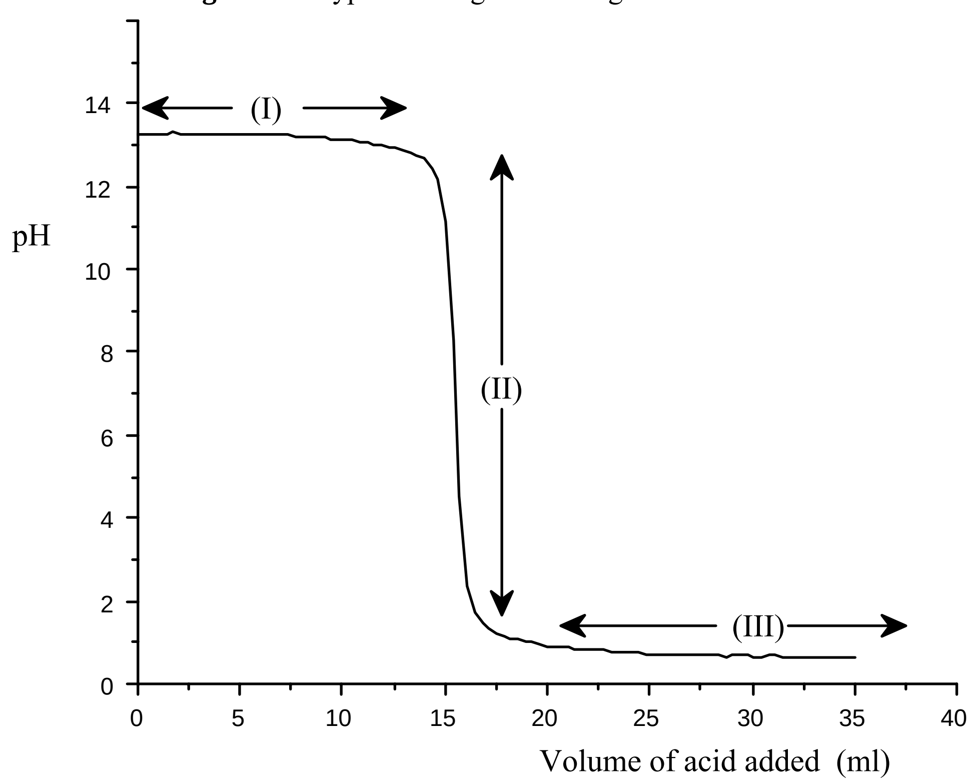
The tasks used in this study are outlined in Table 1 and were designed to provide an overlap of the concepts in different contexts to provide triangulation of the data. For example, the students' ideas about pH and the representations they used to describe acids and bases were elicited from all tasks. The tasks were completed outside the classroom, in two sessions with Tasks 1, 2 and 3 (Interview-about-events and drawings) carried out together, while Task 4 (POE and drawings) was completed approximately one week later. The interviews lasted approximately 30 minutes each. Data collected from the first set of tasks were used to direct questions in the second interview. Students' responses were audio-taped and transcribed, and a number of drawings and predictions were elicited. Profiles for each student were then compiled that detailed each student's ideas about the acid-base concepts.

In Task 4 (POE and drawings techniques) a pH curve was produced by titrating 15mL of 0.1 M NaOH with 0.1 M HCl. The pH changes during the titration were monitored using a pH electrode interfaced to a computer, with the titration curve being produced in real time on the computer screen as a function of volume of acid added. While all the students had completed a unit on acids and bases and had performed titrations using indicators, they had not performed a titration in which pH changes were monitored. In Task 4, the students were required to sketch the shape of the pH curve they expected to obtain, and to explain, using their knowledge of acid-base chemistry, the reasoning behind their predictions. After making their predictions, the titration was run, and the students were asked to describe aloud what was happening. The students were then asked to compare their predictions with the actual curve, and to try to account for any differences.

A typical strong acid-strong base titration curve is shown in Figure 1. The curve has been split into three parts. The students were asked to describe and explain what they thought was happening in each of these sections.

Figure 1. A typical strong acid/strong base titration curve.



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Results and discussion

Student ideas about pH in tasks 1-3

An overview of students' ideas about qualitative and quantitative aspects of the term 'pH' is shown in Table 2. Students were all familiar with the term pH, though three maintained the view that pH applied only to acids. Only one student was not fully familiar with the numerical pH values associated with acids, bases and neutral substances. The most common description of pH was that it either measured the 'strength' of an acid or base or the amount of acid or base present. In each case the students described strength as how powerful or reactive a substance was. All students described the pH scale as inverse, with more acidic solutions having lower values, but few students understood the logarithmic nature of pH.

Table 2. Summary of students' ideas about pH.

Aspect	Number of Students
Familiarity with the term '*pH'*	16
Qualitative aspects of pH:	
• Distinguishes acids and bases	13
• Measures acidity only	3
• Measures 'strength'	6
• Involves ions	4
• Indicator changed color at pH 7	14
Quantitative aspects of pH:	
• Numerical values given	15
• Inverse nature of scale	5
• Logarithmic nature of pH	6
Numerical definition of pH:	
• Defined as $-\log [H^+]$	2
• Includes concentration term	4
• Includes logarithm term	3
• Includes amount of acid	1

Several students gave quantitative descriptions of pH, with four students associating it with concentration and six describing it as logarithmic. However, only two students defined pH as pH $= -\log [H^+]$ and only one of these was able to explain correctly the hundred fold difference in H^+ concentration between the pH 3 and pH 5 solutions, despite all students having had instruction that had emphasized the use of the equation, including several simple calculations of pH values from H^+ concentrations. For most students pH was a linear scale and they applied this logic to answer questions that related pH to other acid-base phenomena, such as neutralization. Only four students mentioned ions in their descriptions of pH and all the students had considerable difficulty explaining how the pH values related to the actual substances in terms of the particles present. The profiles of the individual students showed that there was little consistency between student ideas with respect to the quantitative and numerical aspects of pH and their qualitative ideas.

Another interesting feature was that all the students in Task 2 suggested that the indicator would change color when the solution became neutral. For many of the students all indicators changed color at the same pH value and this was invariably at pH 7.

So why is pH so poorly understood? Kolb (1978, 1979) described the potential pitfalls to learning about pH as being due to the inverse and logarithmic nature of the scale. Hawkes (1994)

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has argued that texts and teachers are misleading or inaccurate in their presentation of the concept of pH in that they fail to describe the approximate nature of the scale by omitting descriptions of the activity of the hydrogen ion. Introductory chemistry texts tend to concentrate on the solution of numerical problems rather than on understanding the concept of pH. This, Hawkes suggests, leads to numerical answers to pH calculations that differ substantially from experimental reality. The treatment of pH by texts is also unsympathetic to any difficulties that students might have with the concept. For example, in the teacher's edition of the Wilbraham et al. chemistry text (1996), teachers are advised that, "*For students who have no concept of logarithms, explain that pH is found by taking the negative of the power (exponent) of the hydrogen ion concentration and expressing it as a whole number*." (p. 541) Students, who have no concept of logarithm, can have no adequate conception of pH at this level. The Wilbraham text contains the implicit assumption that telling somehow equals knowing or understanding, a belief that permeates much introductory chemistry.

The findings of the present study confirm this. Though several students defined pH as being "$-\log [H^+]$" or were able to determine correctly the relationship between pH values and the hydrogen ion concentration of a solution, only one student could relate the concept of pH accurately to an actual solution. That students can perform numerical calculations in chemistry, without the requisite conceptual understanding has been widely described in the literature (see for instance, Nurrenbern and Pickering, 1987; Lythcott, 1990; Sawrey, 1990) and this seems to be the case with pH.

The findings of this study show that students do not generally understand that pH: 1) is a measure of concentration; 2) is not a measure of 'strength' nor of 'powerfulness'; and 3) is a logarithmic, not a linear scale. This, of course, has important implications for teachers, textbook writers and chemistry curriculum developers.

Student ideas about neutralization from tasks 1-3

Students in the study were all familiar with the term '*neutralization*' and all described it as some form of interaction between an acid and a base. Two students believed that acids were inherently more 'powerful' than bases and would have a greater influence in the process. Most students suggested that substances with pH values of 7 were neutral. Six students described the process of neutralization as the physical mixing of an acid with a base and named no products, drew no equations, and represented the process diagrammatically with unreacted chemical species. Ten students labeled neutralization as a chemical reaction, six gave considerable detail, identifying the reacting species, naming the products as water and salt, and explaining it as a chemical interaction symbolically in equations. Three students described the formation of new products by the addition of an acid species to a base species, but did not identify the products, nor could they represent the process with an equation. Their representations of sub-microscopic events simply showed base particles attached to acid particles. A summary of the students' ideas about neutralization is shown in Table 3.

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Table 3. Summary of students' ideas about neutralization.

Aspect	Number of Students
Familiarity with the term '*neutralization*'	16
Substances with pH 7 are neutral	15
Neutralization as interaction between acid + base	16
Interaction as	
• Physical mixing	6
• Chemical reaction	10
Interaction between	
• Unspecified chemicals/molecules	10
• Ions or charged particles	5
• Hydrogen/hydroxide particles	5
Products of neutralization	
Acidic product	2
Neutral product	13
Conditions for neutral product	
• Equal amounts of acid and base	9
• Equal 'strength' of acid and base	3
• Equal 'concentration' of acid and base	1

Several studies have highlighted the difficulties that students have with the concept of chemical change (Andersson, 1986, 1990; Hesse and Anderson, 1992). The Andersson studies classified student explanations of chemical change into five categories: a) its just like that; b) displacement, in which the products are displaced reactants, for example two substances simply mixed; c) modification, in which the products are modified forms of the reactants, for example sawdust made from wood; d) transmutation, in which an entirely new substance is formed, for example gold from lead; and e) chemical interaction, which is the scientifically accepted view. Student descriptions of neutralization all fell into categories of the Andersson classification scheme, with majority falling into the displacement and modification categories.

Many students described neutralization as a simple mixing of acid and base, with no interaction between the particles, and with the neutrality of the product being determined by the relative numbers of particles. From this perspective, the product of a neutralization reaction still contained the acid particles that had not interacted, corresponding to a displacement view of chemical reactions. Other students described neutralization as a process of dominance of acids over bases. The acids, being inherently more powerful than bases, simply dominated the bases. Few students described neutralization as a chemical interaction. All these findings have important implications, as even after instruction students do not understand some fundamental ideas about neutralization and chemical change, despite being familiar with much of the related terminology. Clearly, given student difficulties with such fundamental ideas, it would be interesting to examine what they thought was happening during a titration.

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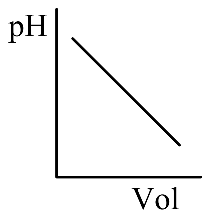
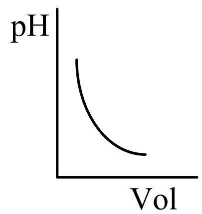
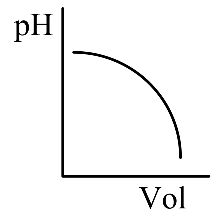
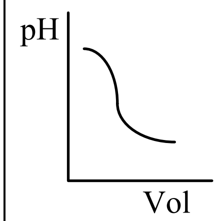
Student predictions of pH changes during a titration: task 4

The predictions made by the students about the pH changes during a titration are shown in Table 4 and their responses were categorized into four general shapes: concave, convex, linear and S-shaped.

Table 4. Student predictions of the titration curve.

Shape	Linear	Concave	Convex	Step
Prediction				
Number of students	8	4	2	2
Variations	2 students: pH stopped at 7. 1 student: pH went level at 1.		1 student drew 2 lines	

All students predicted that the addition of acid would cause the pH to fall, with the majority of the students predicting an immediate and rapid decline in pH. The reasons given were generally that as acids have low pH values and bases have high pH values, adding an acid would naturally lower the pH value. For example, one student who predicted a linear decline as the acid was added

Student: *"... it's forming an acid... bases have a higher number and acids have a lower number, so the pH value will fall..."*
Interviewer: "*So what do you think the pH is measuring?*"
Student: *"... the amount of acid present..."*
Interviewer : *"Could you draw what you would expect to be in the container when, say, 10 mL of acid have been added to the 15 mL of base?"*
Student: *"... I'll try (draws un-reacted H^+ and OH^- ions)"*

This was a typical response. Of the students who predicted an S-shaped curve, one student simply recalled the shape from reading the textbook and was unable to explain the shape. Only one student gave an acceptable explanation for the S-shape.

Student explanations for the pH changes during the titration

After making their predictions the titration was carried out. Student explanations for the shapes of sections I-III of the titration curve revealed important non-scientific alternative ideas about neutralization, pH and the nature of chemical reactions and are summarized in Table 5.

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Table 5. Student explanations of the sections of the titration curve.

Explanation	Number of Students
Section I	
Approximately level section of curve due to:	
• no reaction	4
• reaction not yet started	7
• base dominating acid	1
• base particles outnumber acid particles	1
• immediate reaction leaving excess OH^- ions	3
Section II	
Sudden change in pH due to:	
• reaction suddenly occurring	5
• acid dominating	2
• acid particles outnumbering base particles	4
• $[OH^-] \approx [H^+]$, adding acid causes large changes in $[H^+]$	3
• no explanation	2
• indicator would change color at pH 7	11
• indicator would change color at pH less than 3	4
Section III	
Approximately level section of curve due to:	
• reaction has finished	4
• acid dominates	1
• acid particles outnumber base particles	8
• $[H^+] \gg [OH^-]$	3

In Section I, most students were very surprised to see that the pH value remained approximately constant as the acid was added and several questioned whether the equipment was functioning properly. To account for the non-changing value of pH about half of the students explained that despite the acid having been added, the reaction had not yet started. A further quarter of the students suggested that no reaction was occurring. One student considered the neutralization to be a battle of dominance between the acid and base, while another described the pH as constant due to there being more base particles present than acid particles. Only three students suggested that the acid and base were actually reacting during the first part of the titration.

The sudden drop in pH value near the endpoint in Section II drew audible gasps of surprise from many students. To account for the sudden drop in pH, approximately one third of the students described the reaction as suddenly starting to occur. One quarter of the students described the acid particles as outnumbering the base, while two students suggested that the acid was simply dominating the base. Only three students correctly explained that the concentrations of acid and base were approximately equal, so that on adding more acid, there would be a large change in $[H^+]$ and consequently in pH. Only one student invoked the logarithmic nature of pH to explain dramatic change in pH. When asked about where the indicator would change color the common answer was at pH 7 though a quarter of the students thought that it would not change until the solution had become acidic i.e. in section III of the graph.

Half the students described the leveling of the pH in Section III, as resulting from an excess of acid particles, and each of these students described a physical mixing of acid with base and

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not a chemical reaction. A further quarter of the students described the reaction as being finished. Only three students described an increased concentration of H^+ ions resulting from the reaction and the removal of virtually all the OH^- ions.

Overall, seven students described a time-dependent nature for the interaction of an acid with a base to account for the shape of the curve, while five students described the process as being due to one type of particle outnumbering another with no interaction. Two students described a dominance effect with the acid being inherently “stronger” than the base and only two students described a chemical reaction that removed the OH^- ions and left an excess of H^+ ions.

The students’ ideas about neutralization and chemical change described in the Task 4 titration were different from those described in the previous tasks, and they appear to have been spontaneous attempts to explain what was for them a discrepant event. These inventions indicate a lack of coherent understanding of the nature of chemical interactions, neutralization and pH. Notably, the use of computers interfaced to pH probes, generally known as microcomputer-based labs (MBLs) provided an efficient tool for probing students’ understanding of neutralization and pH. Previous research with MBLs has largely focused on investigating their use in instructional settings. This research suggests that MBLs, with their real time display of results and almost immediate feedback, when used with prediction - observation - explanation (POE) techniques, can provide a powerful tool for probing student conceptual understanding of a variety of topics. Student understanding of other areas of chemistry could be similarly investigated.

Conclusions and implications

The topic of acids and bases is conceptually dense and requires an integrated understanding of many areas of introductory chemistry, such as the particulate nature of matter, molecular kinetic theory, the nature and composition of solutions, atomic structure, ionization, ionic and covalent bonding, symbols, formulae and equations, equilibria and collision theory. This study has indicated that, when conducting a titration, students’ conceptual knowledge of acids and bases lacks both coherency and predictive accuracy and that many students have considerable difficulty understanding the underlying chemistry.

A contributing factor to the conceptual density of the topic, and consequently to well-documented student difficulties, is the tendency of introductory texts to be inclusive of all acid-base phenomena rather than being selective (Carr, 1984; Drechsler and Schmidt, 2005; Furio-Mas et al., 2005). Students are typically presented with an account of the properties or operational definitions of acids and bases, followed by the conceptual definitions, acid-base strength, neutralization, titrations, pH, indicators, acid-base equilibrium and buffers. Included in this coverage is a significant amount of complicated, confusing and sometimes conflicting terminology (Schmidt, 1997; Drechsler and Schmidt, 2005) and large numbers of numerical problems. Zumdahl (1990), for instance, has condensed the material into one chapter of 30 pages, while Dorin (1987), takes three chapters and 67 pages for the same material. In both cases, the ‘coverage’ is encyclopedic in nature

Analyzing the presentation of acids and bases in textbooks, de Vos and Pilot (2002) portrayed a complex and multi-layered topic that, like many areas of chemistry, resulted from the historical development of the content itself. In their analysis they noted that acid-base chemistry contained material from six different layers or contexts and that much of the reason for the conceptual complexity of acid-base chemistry was that the different layers had simply been added to previous layers without any restructuring of the content. In the USA, the topic of acids and bases is typically allocated three weeks of time in introductory chemistry and is studied

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towards the end of the academic year, (see for example, Nakhleh, 1990), as it requires the prior 'coverage' of many related topics.

Further increasing the conceptual density of the topic are the ways that various models of acid-base chemistry are introduced. Following their historical development, the Arrhenius model is presented first, then Brønsted-Lowry and finally, though not in as much detail, the Lewis model. The issue of which acid-base models to include in introductory chemistry has long been controversial and debate about which models to introduce at which level of chemistry has been ongoing since they were introduced in the 1920s and is still a contentious issue (see for instance, Hall, 1930; Briscoe, 1940; Johnson, 1940; Alyea, 1941; Luder, 1948; Logan, 1949; DeFord, 1950; Devor, 1954; Carr, 1984; Kaufmann, 1988; Hawkes, 1992; Rayner-Canham, 1994). Proponents of the Arrhenius model note that it is simple (Johnson, 1940), that it accounts for most acid-base phenomena encountered in introductory chemistry (Hall, 1940), and that it should be included in introductory courses for historical reasons (Briscoe, 1940). Proponents of the Brønsted-Lowry model note that the Arrhenius model is very limited (Hammett, 1940; Hawkes, 1992), especially for bases, only applies to aqueous solutions (Naiman, 1948) and that the Brønsted-Lowry theory is useful for explaining other areas of science such as respiration (Devor, 1954). Proponents of the Lewis theory note its more generalized approach, but few advocate its use in introductory chemistry (Luder et al., 1943; Drago, 1974).

Ausubel noted that "*the best way to organize information after it is understood is not always the best way to organize it so that it will be understood in the first place*" (quoted in Bodner, 1992; p 189) and curriculum writers, teachers and textbook writers should heed this advice. It suggests that instructional materials that build on what students already know, rather than on the encyclopedic coverage of what scientists have discovered will be more fruitful. Given the amount of material typically included in the unit on acid-base chemistry, coupled with the inadequate time allocated to the topic almost guarantees a transmission/reception style mode of instruction with an emphasis on 'covering' information in lectures.

A recommendation from this study is that curriculum developers, textbook writers and teachers heed the calls from science education researchers to reduce the quantity of material in introductory chemistry, particularly in the area of acid-base chemistry. The sheer quantity of material introduced; the short time in which it is introduced; the convoluted and vague terminology used to describe acid-base phenomena coupled with the need to relate the material to what students already know, inevitably leads to superficial, short-term learning with little conceptual understanding. Acid-base chemistry provides a wealth of valuable information about the nature of the discipline of chemistry and how chemical ideas develop and progress historically and as such it should be a springboard and not a barrier to further learning.

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