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Students' Models of Matter in the Context of Acid-Base Chemistry

by

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Technical Editor's Note: Figures can be found at the end of this article, as supplied by the author.

Problem Statement

This paper reports secondary students' understandings of acids, bases, and pH which emerged in semi-structured interviews conducted as part of a larger study of the effects of three levels of instrumentation on students' understandings of acids, bases, and pH (1, 2). Students were interviewed prior to performing a series of acid-base titrations, and they were interviewed again after the series of titrations. The verbal data and drawings from these interviews were analyzed to extract common adequate understandings of acids, bases, and pH, as well as common inadequate understandings, called alternative conceptions, of acids, bases, and pH. In this paper I report the four models of matter which students used in their interviews to explain their understanding of acid-base chemistry.

Theoretical Background

The perspective which governed the design of this study is that students construct their own knowledge (3, 4, 5, 6). Students construct their chemical knowledge from many sources: formal instruction, public knowledge available in various forms, prior knowledge of science, practical experiences, and informal sources, such as parents and friends (7). Because students do indeed construct their knowledge by constantly taking in and reorganizing information, one would expect that this knowledge has the potential to change over time. Indeed, studies of students' understanding of motion (8) and gases (9) have found that students of different ages seem to have an understanding of scientific concepts which progress along a continuum from a naive understanding to a more scientifically appropriate understanding. Therefore, a working hypothesis of this study was that the students might have constructed a variety of models of matter to explain chemistry to themselves and that these models at least had the potential to change over the course of the study.

Posner and Gertzog (10) maintain that much of this constructed knowledge can be captured by well-designed interviews in which students are asked to explain a series of events which they observe. Krajcik, Simmons, and Lunetta (11) propose using a semi-structured format for these interviews in which all participants are asked the same set of questions, but the interviewer is also free to ask other questions in order to clarify students' responses to the questions. These interviews are rich sources of information about the student's understanding of chemistry topics.

Description of the Study

Fourteen senior high school students in grade 11 from a large east coast city participated in the study. The students were in the last weeks of a regular first-year high school chemistry course, and they had just completed a unit on acid-base chemistry. The students were selected to have an overall grade point average of 2.80 to 3.20 or to have earned a cumulative chemistry grade of B- to B+. The students in the sample also reflected the ethnic diversity of the school: African-American, Asian-American, Caucasian, and Hispanic. The students were divided into the three instrumentation groups by sex, class period, and grade point average in a effort to provide similar groups. The activity performed by each individual member of each instrumentation group consisted of a series of three acid-base titrations: strong acid-strong base, weak acid-strong base, and polyprotic acid-strong base. Hydrochloric, acetic, and phosphoric acids were used, and the base in each case was sodium hydroxide. However, students in each group used a different type of instrumentation to perform the titrations. Students in the first group used a chemical indicator, students in the second group used a pH meter, and students in the third group used a microcomputer-interfaced pH probe.

Students were interviewed individually prior to the series of titrations to probe their understandings of acids, bases, and pH, and then they were given an individual orientation to the type of instrumentation they would use to perform the titrations. Following the completion of the titrations, students were again interviewed to probe their understandings of acids, bases, and pH.

The interview was based on the semi-structured format (11) in which students responded to a series of scripted questions about the phenomena which they observed in the interview. The researcher asked every student the same set of questions; however, the researcher was also free to pursue other lines of questioning if it became necessary in order to clarify the student's understanding of the phenomenon. The initial interview consisted of four sequences of examples and demonstrations. The final interview was a parallel form in which the examples were changed and the fourth sequence demonstration was reversed so that the acid was added to the base. The interviews and the results of the larger study are described in detail by Nakhleh and Krajcik (1, 2).

First interview sequence. The student was shown four small bottles marked dilute acid, dilute base, pH 4, and pH 11 respectively. In each case the student was asked to tell what he or she knew about acids, bases, or pH. Since the pilot study had revealed possible weak conceptions of molecules, atoms, and ions, each student was asked to draw on the interview data sheet what they might have seen if they could have looked through a very powerful magnifying glass at the solutions of acids, bases, pH 4, and pH 11.

Second interview sequence. The student was shown five labelled bottles or cans of commercial products, such as ammonia, vinegar, dishwashing detergent, baking powder, and Coca-Cola. The student was then asked which of these products might contain an acid or a base. Each selection was then discussed as to why it might contain an acid or a base. The next section of this sequence was a presentation of five small bottles labelled with the formulas HCl, NaOH, CH_3COOH, NH_3, and NaCl. The student was asked to select which ones of these were acids or bases, and then the reasons for the selection were discussed.

Third interview sequence. The student observed the changes that occurred when an acid and base were mixed in the presence of phenolphthalein. The student was shown small bottles marked dilute acid (0.1 M HCl) and dilute base (0.1M NaOH). The student observed as 50 mL of the acid was poured into a beaker, and some phenolphthalein was added. The student was then probed to assess his or her understanding of the role of the phenolphthalein. If, after a series of questions, the student was still unsure, the interviewer stated that the phenolphthalein would change color if any change occurred in the solution. The base was slowly added to the acid, swirling the liquid in the beaker so that the student could observe how the pink color formed and faded before changing color permanently. The student was then asked to describe what had happened to the acid, to the base, and to the pH and to explain what was in the beaker after all the base had been added. The student was also asked to describe what they would see if he or she could look in the beaker with a powerful magnifying glass.

Fourth interview sequence. The student was shown two opposite graphs of pH versus volume of base added and asked to select which graph best described what had happened to the pH when the base was added to the acid in the beaker. The student was then asked to explain why he or she had selected that particular graph. The student then circled and labelled the part of the graph that showed the system was acidic, the part that was basic, and the part that was neutral. The student was also asked to explain what was happening to the acid and base in the vertical portion of the graph where neutralization occurs. Finally, the student was asked to explain what situation the second graph described.

Four experts were given the same initial or final interview as the students. Two of these experts held a Ph.D. in science education, with particular expertise in chemistry, one was finishing a Master's in science education, and one held a Ph.D. in chemistry. All of the experts agreed that the interview effectively covered the important topics in undergraduate acid-base chemistry.

Analysis of the Interviews

Molecular concepts in interview verbalizations. The verbal data of the interviews were analyzed to identify the underlying models of matter which students used to explain the phenomena which they observed during the interviews. Most of the students exhibited poorly formed molecular concepts, and they had great difficulty in using molecular models and in thinking in terms of the molecular nature of matter. For example, in the initial interview (page 3), #0204 found it very difficult to to verbalize anything about the molecular level.

> R: Now if you had a big magnifying glass, a really really good magnifying glass that you could magnify hundreds of millions of times, and we looked at this [acid] solution in here with that magnifying glass, what do you think you might see?

S: ....

R: Do you think you'd see anything?

S: Probably not because it wouldn't be, I mean it's clear as you can see but, OK, you say how big is this thing?

R: The magnifying glass is so powerful that you can see anything you want to. Whatever you think you might be looking at you can see it.

S: Um. I don't think so because it's stronger than water so, and water'd be like a clear you know just plain and I don't think you, you might see the liquid but this is stronger like I said so I don't think you'd see much.

R: If you were looking at just plain water what would you see?

S: Well, you'd see the water because it's clear and it's clean so I don't think anything'd be in it, you know.

R: What does water look like up close like that, really up close?

S: Oh, I don't really know, depends on the . . . ., just look like a liquid you know.

Eventually the student decided that the liquid could contain little particles which "could be circular or spindly" (initial interview, page 5). In the final interview (page 1) the same student had less difficulty in articulating a view that the solution contains particles of some kind.

R: If you had a magnifying glass, and . . . . you could look into this bottle of acid what would you see?

S: I'd probably see the particles that it's made of. You know, the um, you know, everything has a shape or stuff that they consist of and what they look like is what I think I'd see.

Molecular concepts in interview drawings. The interview drawings confirm the explanations given by the students verbally. In general, the students fall along a spectrum of conceptual development from a macroscopic, nonmolecular view of matter to an increasingly molecular and ionic model of matter.

In the initial and final interviews, students were asked to pretend that they had a very powerful magnifying glass which could magnify 100 million times; then they were asked to draw what they would see if they could look into a solution of dilute acid, a solution of dilute base, a pH 4 solution, a pH 11 solution, and the solution of acid and base after neutralization. These drawings were assigned to categories according to the student's increasing perception that the solutions in the beaker contain a mixture of water molecules, positive ions, and negative ions.

In Table 1 the molecularity of the group's concepts was estimated by calculating a weighted coefficient which enabled comparison of the groups. Each group was assigned one point for every group member holding a particle conception of the solutions, two points for a molecular conception, and three points for a partial ionic conception of the solutions. A ratio value was obtained by dividing each group's total score by 15, which would be the score if every group member possessed a partially ionic conception of the solutions. The total score for the pH meter group was divided by 12 because one student had withdrawn from the study. The term 'partial ionic' is used because the students drew the charged groups as being attached to molecules. No drawings represented the ions as unattached, independent particles. Table 1 indicates that two groups moved toward more appropriate conceptions of matter. The microcomputer group made the most substantial shift, and the pH meter group apparently showed no conceptual change during the treatment.

[Insert Table 1 about here.]

The four models of matter are illustrated in Figure 1. It is important to note that these drawings were done in pencil and were very difficult to duplicate legibly. Therefore the drawings in this paper are representations of the students' drawings.

Continuous model of matter. The students in this category demonstrated a simplistic, undifferentiated view of matter. When asked what a solution of acid or base would look like in a very powerful magnifying glass, they drew waves, bubbles, microbes, or shiny patches (see Figure 1).

[Insert Figure 1 about here.]

Students in the first category also had difficulty verbalizing what they thought was in the liquid; as shown in the preceding examples, they would typically respond that the solution would just look clear, like a liquid. The following sequence from a initial interview with #0113 (page 3) illustrates this category:

> R: You have this magnifying glass that's really powerful. We're just pretending that we have a very, very powerful magnifying glass and we can see right down into that liquid. . . . You can see really, really close. What, what would you see?
>
> S: Probably some substances. You know, probably like a different color like vinegar, if you mix vinegar with water, you'll see a different different kind of you know feature if you if you looked into it real carefully.
>
> R: Well, what would that feature be made up of? If you could get really close to the feature so you can see individual things, what would be, what would you see?
>
> S: Some part of it will be kind of shiny, some of it will, you would, you would imagine that I mean you could you would kind of see a different color in it, but it's not on, it's not really there, but you can you could see it with your, I mean when you look at it real close, um, you could see probably see like a line going through like they're following the, the vinegar or something like that you know, like if you don't mix it, if you don't stir it up with a spoon or something you probably see the line that's going through it.

In the initial interview, 21% of the students fell into the continuous category, and even by the final interview, 14% students, both in the chemical indicator group still represented the solutions as composed of continuous matter. Two of the students from the chemical indicator group remained in this category throughout the study.

Figure 2 shows that #0302 from the microcomputer group moved from a continuous representation of a clear liquid filled with bubbles, to a partially ionic representation where the circles now stand for molecules. The charges for acids and bases are shown outside the circle, and the student does not indicate how these charges are distributed. The student has drawn base molecules as smaller than acid molecules, a proposition which is also reflected in his or her verbalizations in the interviews.

[Insert Figure 2 about here.]

Particulate model of matter. Students with this viewpoint believed that matter is made of tiny particles but did not articulate any clear sense that these particles are molecules. Students in this category drew irregularly shaped particles of different sizes which looked like tiny pieces which had been broken from a continuous solid (see Figure 1).

During the interview, students in the second category would verbalize that the solution contained particles, but they would have difficulty in explaining what these particles were like. A sequence from the initial interview of #0315 (page 2) in the microcomputer group illustrates this point:

> R: If you were to look at an acid very closely with this big magnifying glass, . . . if we did have such a very very powerful one, millions and hundreds of millions of times magnified, um what would you see?
>
> S: Well, I think if we, you would see, um whole bunch of chemicals, um that are, OK I guess you couldn't describe them, whole bunch of chemicals, different chemicals put together that are strong and therefore um I can't, I can't explain the other, can't explain.

In both the initial and final interviews, 36% of the students drew this type of particulate structure. Of the five students in this category, four remained in the category throughout the course of the study and the other one moved to a higher category.

As Figure 3 indicates, a student in the chemical indicator group, #0110, shifted toward a more ionic conception of acids and bases. In the initial drawing he has represented air bubbles and atoms in the liquid, but he does not make the connection that these atoms must be ions. In response to the question of what he would see under the magnifying glass, he replies "I don't know. Atoms or something. Some little bubbles I guess" (initial interview, page 5). In the final interview he replies to the request to state what he knows about bases by saying "I know acid is corrosive. And they neutralize base, and they produce a hydrogen ion in water, and it tastes sour" (final interview, page 1). In the final drawing he no longer represents bubbles; he draws hydrogen and oxygen atoms. Note that, although he mentioned the term "ion" in his conversation, he failed to indicate ions in his drawings.

[Insert Figure 3 about here.]

Molecular model of matter. Students would draw clearly spherical or circular particles which were more or less uniform in size and shape (see Figure 1). Some students even drew a ball-and-stick representation of the molecules to show how the atoms of the molecule were bonded together.

In the interviews, students in the third category were able to use the term molecule and discussed the solutions in terms of molecules, but they did not evidence any understanding that these solutions contained mostly positive and negative ions. The following exchange in the initial interview with #0114 (page 5) illustrates this point:

> R: Draw, in any blank space there, what you think an acid would look like if you could see it up close and personal.
>
> S: I just think of fizzing and little circles that I call molecules. Bumping into one another, closely.
>
> R: What's in those molecules? You're talking about molecules, can you be more specific?
>
> S: Um, compounds that make up the acid like um well like the NaOH, we used that and it's like Na, sodium, and oxygen and hydrogen, all of those together making up that acid.

In the initial interviews 43% of the students drew molecular representations of the solutions. However, in the final interviews this number dropped to 21% of the students because two students moved to an ionic representation and one student dropped back to a particulate representation.

Figure 4 illustrates this change in representation from molecular to partially ionic. In the initial interview, this member of the microcomputer group, #0302, replied to the question of what you would see with an imaginary magnifying glass in an acid solution by saying "probably some sort of molecules or um elements that combine with each other, elements and molecules, and they take electrons from that, they just switch them over and change to, that's what changes it to something different" (page 3). This student then drew a ball-and-stick representation of a molecule with no charges shown. In the final interview the student stated that "you'd have a hydrogen ion in there somewhere" (page 2). The final drawing shows a ball-and-stick representation of molecules which have positively and negatively charged parts.

[Insert Figure 4 about here.]

Partially ionic model of matter. This model is based on the realization that acid and base molecules in solutions can break into positive and negative particles called ions (see Figure 1). The most appropriate representation of the solutions would have shown the acid or base as being broken into positive and negative ions and would have shown water molecules being attracted to the charged ions. Students, however, represented the ions as attached to the parent molecule so that essentially the acid or base molecule had charged ends. Also students did not represent the water molecules in their drawings.

In the interviews students were able to verbalize that charged particles were present in the solutions, but they were unable to state that the ions were physically separate particles. The following final interview with #0301 illustrates this point:

> R: If you were to look at this acid with a magnifying glass so that you could really see what was in the solution there, what would you see?
>
> S: I'd probably see a formula, and it would have, you know, if it was the like a compound you'd see your little circles and your um bonds going off at angles, and you'd have a hydrogen ion in there somewhere, or a hydrogen in there somewhere.
>
> R: Would you draw that please, right here.
>
> S: Alright, depending what you have, you just have um your circles and any depending what formula it is, somewhere in there you'd have hydrogen, some form of hydrogen.

R: Would that hydrogen be an ion or would it be

S: Um, probably not.

In the initial interview, no students used a partially ionic representation of the solutions. However, in the final interview, 29% of the students drew partially ionic representations of matter because two students in the microcomputer group and one student in the chemical indicator group moved into that category.

Conclusions

Acid-base chemistry is an essential component of secondary and undergraduate chemical education because of the wide commercial applications of acids and bases and because of increasing public awareness and concern over environmental issues. However, the interviews in this study disclosed that the students were unable to fully understand the acid-base chemistry because they tended to have weak understandings of the particulate model of matter and of how that model relates to some of chemistry's classification systems, such as molecules, atoms, and ions. Students also were unable to move easily from verbal descriptions of these molecular level concepts to representing these concepts in drawings. Some students did change their models of matter during the course of the study, but their inappropriate understandings were resistant to change, and no student developed a completely appropriate understanding of the role of ions in aqueous solutions. These findings have several implications for chemistry educators at all levels.

Educators should actively probe their students for signs of inappropriate understandings by a variety of techniques. Direct questions, predictions of the outcome of demonstrations, and explanations of demonstrations are ways that educators can probe undergraduates' ideas during a lecture. Opinion polls and class discussions of historical models contrasted with the current model can be used at the secondary level and in small undergraduate classes. Educators at all levels should provide opportunities for students to create or interpret representations of a chemical event on a molecular level. Finally, educators should realize that time is required for students to appreciably change their understanding of the particulate nature of matter. Therefore, students should be exposed to these ideas in both secondary and undergraduate chemistry.

Students must understand that they do indeed construct their own chemical knowledge and that the process of construction is often long and laborious. Therefore students have a responsibility to practice and reflect upon the knowledge presented in instruction. Both students and teachers need to work together to ensure that the understandings which students generate are scientifically acceptable and provide a firm foundation for further progress in chemistry.

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Table 1

Molecular Concepts of the Students as Expressed in Interview Drawings

Group	Number of Students				
	Continuous Concept	Particulate Concept	Molecular Concept	Ionic Concept	Molecularity Coefficient
Initial Interviews					
Chemical					
Indicator	2	1	2	0	0.33
pH Meter	0	2	2	0	0.50[a]
Microcomputer	1	2	2	0	0.40
Final Interviews					
Chemical					
Indicator	2	1	1	1	0.40
pH Meter	0	2	2	0	0.50[a]
Microcomputer	0	2	0	3	0.73

[a] Based on four group members.

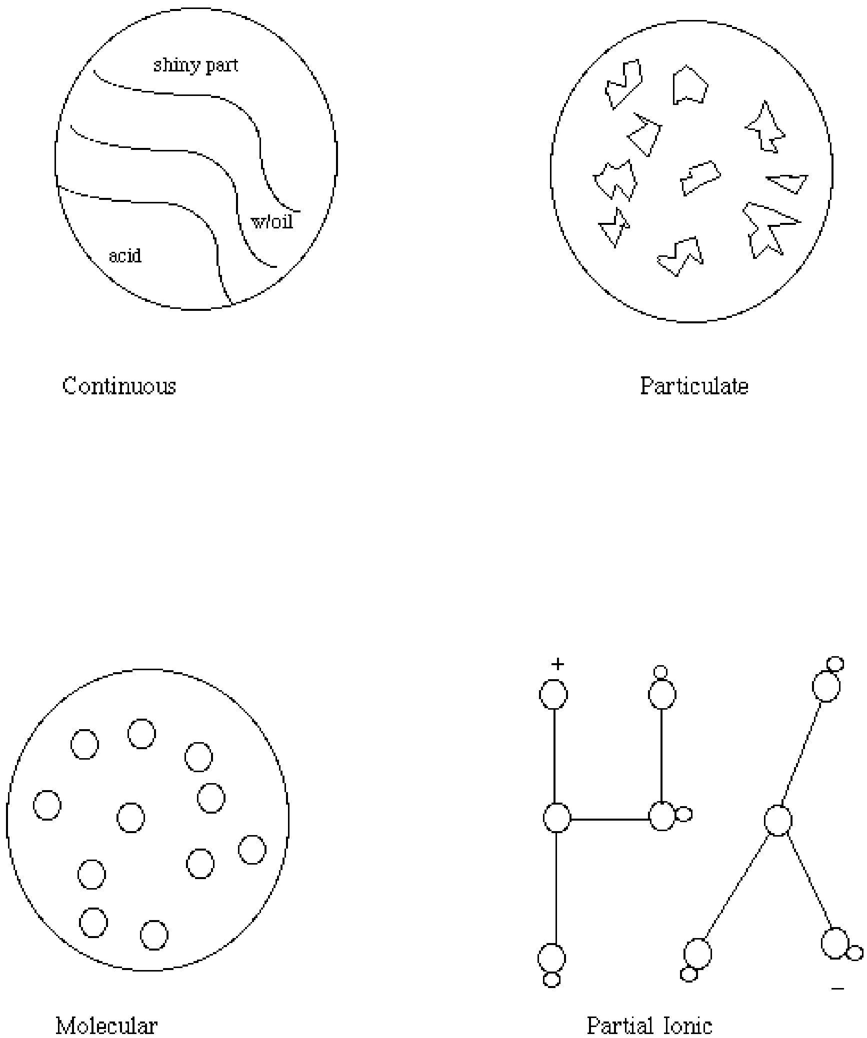

Figure 1. Students' drawings of acid solutions which reveal students' model of matter. Figure has been redrawn.

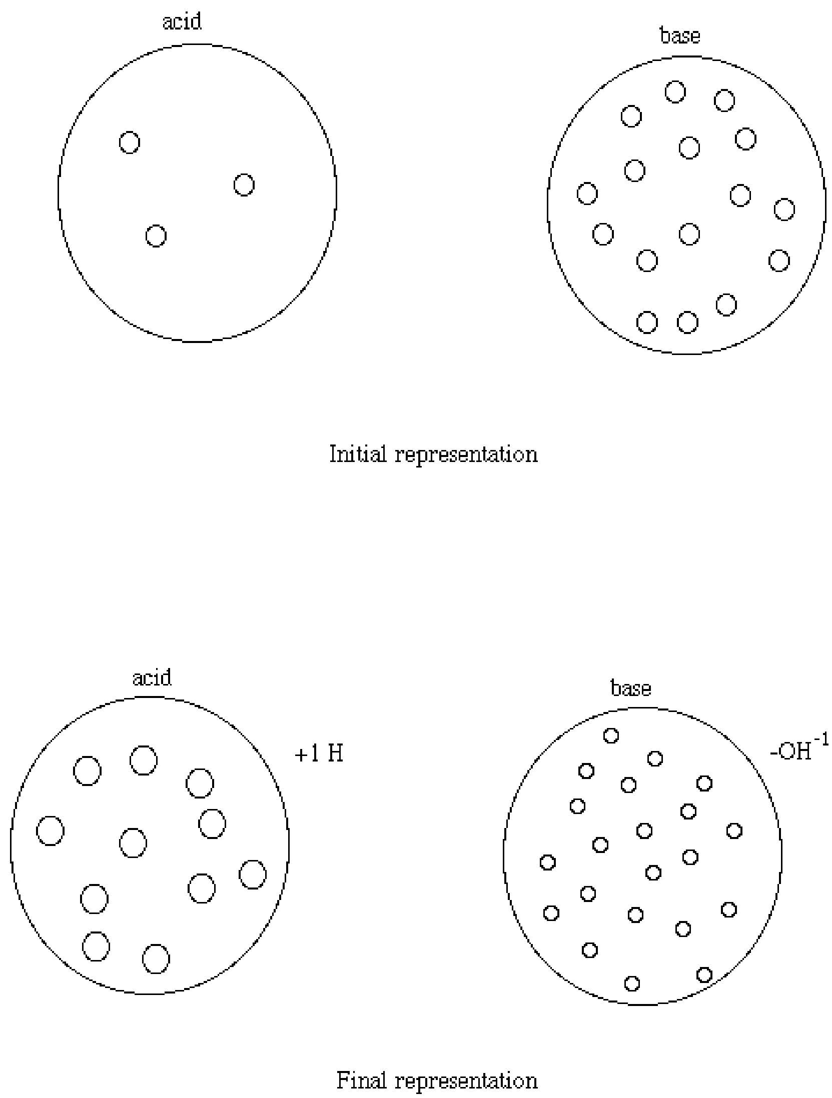

Figure 2. Pre and post representations of acid and base solutions by #0302. Figure has been redrawn.

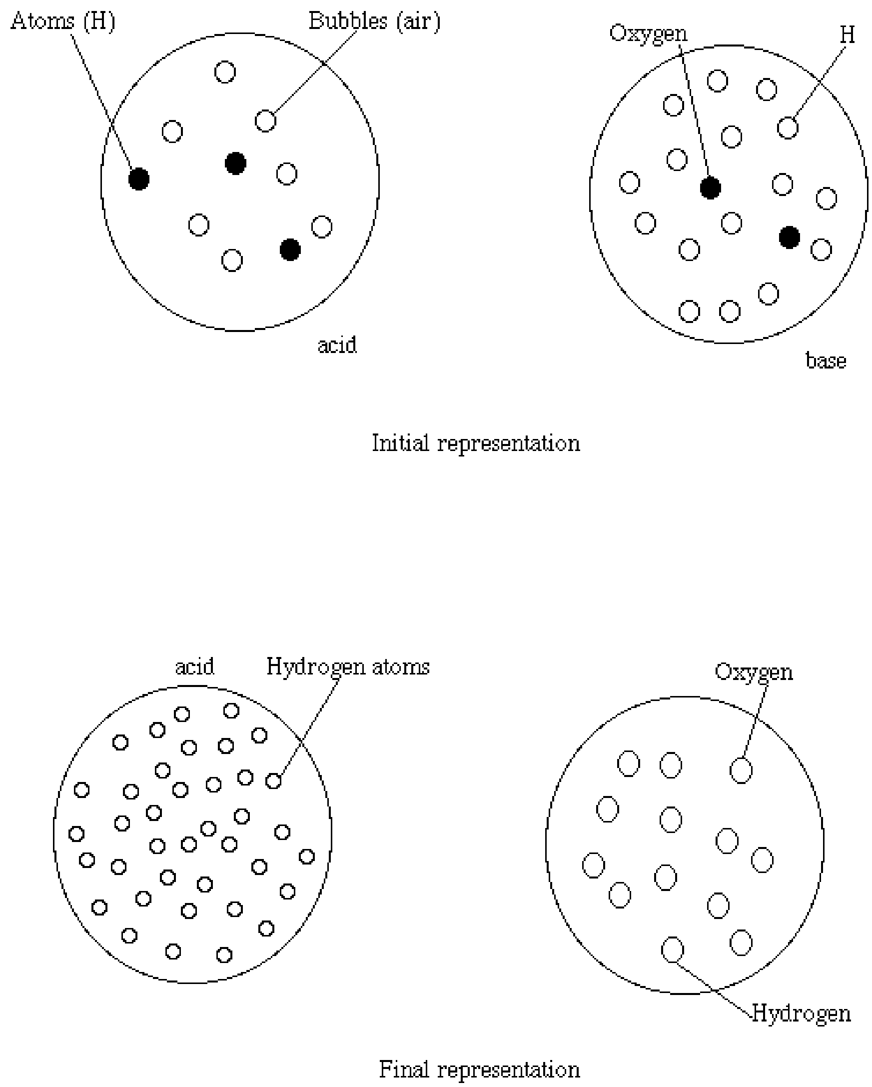

Figure 3. Pre and post representations of acid and base solutions by #0110. Figure has been redrawn.

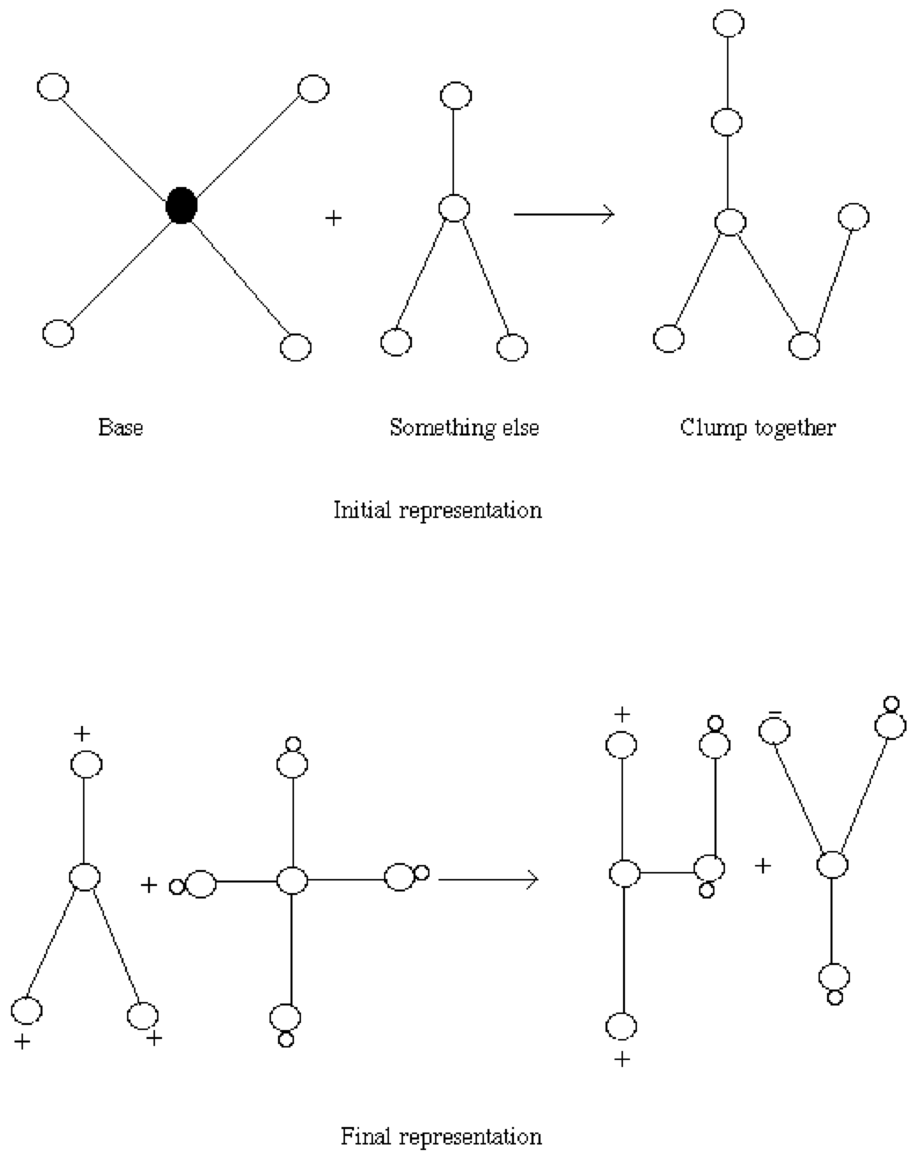

Figure 4. Pre and post representations of acid and base solutions by #0301. Figure has been redrawn.