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# Promoting Student Development of Models and Scientific Inquiry Skills in Acid−Base Chemistry: An Important Skill Development in Preparation for AP Chemistry

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Supporting Information

**ABSTRACT:** In this study, two groups of 11th grade chemistry students ($n$ = 210) performed a sequence of hands-on and virtual laboratories that were progressively more inquiry-based. One-half of the students did the laboratory sequence with the addition of a teacher-led discussion connecting student data to student-generated visual representations of different acid−base models (Arrehenius and Brønsted−Lowry). Students were assessed for perceptions about their learning as well as their understanding of acid−base models. The results showed improvement in 79% of the students in understanding acid−base chemistry following the inquiry laboratories as well as improved mental models explaining acid−base chemistry in 72% of the students. The students also responded favorably to the addition of virtual laboratories, with 77% reporting improved understanding of the chemistry as a result of the addition of the technology.

**KEYWORDS:** *High School/Introductory Chemistry, Acids/Bases, Misconceptions/Discrepant Events, Inquiry-Based/Discovery Learning, Internet/Web-Based Learning, Laboratory Instruction*

## INTRODUCTION

Acid−base chemistry is an example within chemistry in which there are multiple scientific models to explain the phenomena on an atomic level. The challenge presented in teaching this content is that students prefer to use the simplest model necessary to explain a phenomenon and only use more sophisticated models when their simpler explanations break down.[1] This research finding about students' use of scientific models is also seen when students attempt to explain acid−base chemistry using the Arrehenius model but are unable to transition to describing atomic phenomena using the Brønsted−Lowry model.[2,3]

This particular body of knowledge is also riddled with student alternative concepts built from experiences both in school and outside of school,[4] as well as the shift in the meaning of language when used in a chemical context.[5] Students think fruits are basic and bases do not contain hydrogen.[4,6] Students think that neutralization always results in a neutral solution and that a salt solution does not contain hydronium or hydroxide ions.[5] In another study, ninth graders held onto their alternative concepts about acidity or basicity of a solution based upon their macroscopic observations of acids or bases, rather than an understanding of the ions or another model of acid−base chemistry.[7]

The challenge facing every chemistry teacher is to transition students from the macroscopic observations that they make in the laboratory to a clear mental model based upon the atoms.[8] Unfortunately, as the research mentioned above shows, students have a difficult time transitioning away from their mental models about acids and bases even when instruction explains a more sophisticated model. In order to bring about conceptual change, students must have meaningful experiences that make them reconstruct their mental models.[9]

The new standards for advanced placement (AP) chemistry have incorporated findings from decades of educational research into pedagogic guidelines. In particular, the first science practice (Science Practice 1) in the AP chemistry course and exam description[10] addresses the practice of students "using representations and models to communicate scientific phenomena and solve scientific problems".[10] Forming scientific models is a critical step in helping students explain the atomic phenomena as it relates to the macroscopic observations that students gather in experiments.[11] Furthermore, students who are challenged to construct their own scientific models are more likely to uncover the holes in their reasoning and be forced to adapt to a more sophisticated model which approximates the scientifically correct models.[1,7]

When students begin a laboratory investigation, it can begin with a question or it can begin with a mathematical problem to solve. Students who have stronger abstract mathematical reasoning skills tend to focus upon a mathematical problem rather than a conceptual question. To explain the logic behind the mathematics or begin with a question, students must have a conceptual understanding of the atomic phenomena and have developed their own mental model. This approach to laboratory design is aligned with inquiry pedagogic approach where students must apply their understanding to solve a problem through the laboratory. When students develop a model that incorporates the concentration of the ions (hydrogen or hydroxide) in solution, they can then create an atomic picture of the ions and how they relate to pH measurements. Alternatively, students can understand what data points to use in the equation to solve the problem mathematically, but they may be unable to connect the data to

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**Table 1. Sequence of Laboratories and Instruction for the Three-Week Acid−Base Unit**

| Curricular Focus | Lab Goal | Type of Lab (Source) | Key Concepts |
|---|---|---|---|
| Arrehenius Model | Titration of unknown acid | Real-time lab, structured (Author: See Supporting Information) | Hydrogen and hydroxide ion concentration |
| Arrehenius Model | Titration of strong base | Virtual lab, structured (ref15) | Titration curve, end point |
| Arrehenius Model and Brønsted-− Lowry Model | Titration of strong acid | Real-time lab, guided inquiry (Author: See Supporting Information) | Titration curve, calculation |
| Brønsted−Lowry Model | Titration of an unknown weak acid | Virtual lab, inquiry lab (ref16) | Titration curve, $pK_a$ from graph |

the phenomena. These students are more likely to successfully complete the calculations for a single lab, but they may be unable to transfer the skill to a similar laboratory with variation. For this reason, these students find inquiry laboratories more difficult than the more directed alternatives.[12]

## ■ STUDY DESIGN

### Participants

In this study, 11th grade students were selected from the general student population in a diverse urban high school over the period of two years. The concept of acids and bases were introduced in eighth grade curriculum; however, the topic was limited to the teaching of the pH scale and for some students the Arrehenius model of acids and bases. In the introductory high school chemistry class, students learned pH scale and calculations from ion concentration as well as the Arrehenius model and the Brønsted−Lowry model.

### Design

The students ($n$ = 100) in the first sample were taught with the curricular focus of understanding each laboratory goal. The second group of students ($n$ = 110) performed the same laboratories, but there was an addition to the instructional sequence. For the second group, each laboratory was followed with a discussion that connected the student data to building a model to explain the ion concentration in the solution. This approach used the laboratory data as a means to build student-developed models of acids and bases. Students worked on models using manipulatives of water molecules that broke apart into a hydrogen ion and hydroxide ion that could be incorporated into visual representations. The students created visual representations of the ions in solution and how they changed throughout the lab. The visual representations served as a formative assessment tool for the students' mental models of acid−base chemistry at each stage of the instructional sequence. This pedagogic approach is based on educational research on how to teach in a manner that overcomes student misconceptions.[8]

## ■ MATERIALS AND CURRICULUM

An overview of the curricular sequence of laboratories is given in Table 1. The curricular choice to alternate real-time and virtual laboratories was based upon the type of laboratory design. The first laboratory was structured with a strong focus on learning how to graph ions in solution as well as connect the ions to the reaction that takes place in a titration. The second laboratory mimicked the first lab, as the base was being added to an acid. However, the second laboratory introduced new equipment in the virtual format with the hope that students would gain confidence in the virtual environment prior to experience with the real-time environment. In the third lab, students performed a guided-inquiry laboratory where they designed the experiment to test an unknown strong acid. The set up mimicked the virtual lab but did not use the same acid. In the final lab, the students designed the lab completely on their own. This laboratory provided students with an unknown weak acid that they must test to determine the $pK_a$. The previous laboratories provided background knowledge for the laboratory design needed in this open inquiry lab. The virtual format allowed students to select the base they used as well as the concentration. There was no ability to use an indicator, but the pH was measured with a pH meter that they have used in the virtual and real-time laboratories preceding the final lab. Students in both groups used the pH probes in the third lab of the sequence. The main difference between the two groups was not the laboratories or the technology used. The difference was the addition of an inquiry-oriented discussion following the laboratory to build on the laboratory experience eliciting student explanations of the data that would reveal the level of complexity in their own understanding of acids and bases. Students were given manipulatives and animations[13,14] to assist them in creating visual representations of their mental model explaining the acid−base chemistry with the ions. The way that the ions were explained and the level of atomic understanding was then a source of further discussion, so students could strengthen their models and fill in gaps in their models.

### Analysis of Curricular Choices

The purpose of this sequence was to provide students with the best learning experiences possible in both the virtual and real-time formats. The introductory laboratory provided students the opportunity to see the nuances of real data as well as the variance of data created by a classroom of student scientists. Whereas in the virtual format the data was very controlled and clean, the virtual format did provide students the opportunity to learn about new lab techniques without negative consequences, such as experimental errors. The virtual format allowed students to repeat an experiment easily within one class period. This instructional choice aligned with the research review by de Jong that cited the positive and negative attributes of virtual laboratories.[17]

### Assessment Tools

The student performance was assessed with two formative assessments in the curricular sequence. The first formative assessment was prior to the guided inquiry and inquiry laboratories. The second formative assessment followed these laboratories. These formative assessments included an open-ended question and the design of an inquiry laboratory where the students had to decide how to identify an unknown acid. The summative assessment was a multiple choice unit test. These assessments were conducted as part of the study and were incorporated into the instruction for the second group to modify the discussion, so student misconceptions were addressed in a discussion with the whole class.

Additionally, students' self-perception about their understanding of acid−base chemistry as well as their attitudes about


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Table 2. Comparison of Coded Responses on Formative Assessment for Two Student Groups

| | Student Responses Coded into These Categories, % | | |
|---|---|---|---|
| Student Group | Described Lab Only | Related to Mathematical Relationship | Connected Mathematical Relationship to Atomic Model of Ions |
| Group 1: All laboratories, without follow-up discussion to develop student models ($N$ = 100) | 75 | 18 | 7 |
| Group 2: Included concept development of models as explicit part of instruction ($N$ = 110) | 45 | 25 | 29 |

Table 3. Comparison of Change in Coded Responses from the Formative Assessment to the Summative Assessment

| | Change in Student Assessment Performance, % | | | |
|---|---|---|---|---|
| Student Group | Improved Score from Below Proficient to Proficient | Improved from Proficient to Above Proficient | No Change in Ranking | Improved in Ranking from Formative Assessment to Summative Assessment |
| Group 1: All laboratories, without follow-up discussion to develop student models ($N$ = 100) | 29 | 22 | 49 | 51 |
| Group 2: Included concept development of models as explicit part of instruction ($N$ = 110) | 28 | 50 | 22 | 78 |

using technology in the classroom. This assessment was included because previous research has shown that students' confidence increased through the use of virtual laboratories in science as well as the perception that they understand the concept better as a result of the virtual laboratories.[18,19]

## RESULTS

### Formative Assessment

Following the second lab in the sequence (Table 1), students were asked: If you have an acid with unknown concentration, what measurements would you need to solve this? This assessment was designed to resemble the questions used in the laboratories without using the terms titration or base. The question was also designed to stimulate students' thinking about measurements used in lab analysis.

The results from this assessment reported in Table 2 show that the majority (75%) of the students surveyed in the first group could only partially describe what they did in lab, but they did not relate it to the analysis of data or the math needed for the analysis. In the second group, who had discussed the data more extensively in connecting it to acid−base models, the number of students who could relate the question to the laboratory was greater and the number of students in this category dropped to 45%. In the first group, 18% were able to discuss the mathematical process needed to analyze the data (MaVa = MbVb) and identify which component was unknown (Ma). Whereas 25% of students in the second group related the data to the mathematical analysis, perhaps because they had a stronger conceptual understanding of the ions in solution and molarity needed for the math. Finally, a small set (7%) of the students in the first group successfully connected the laboratory experience to the mathematical analysis illustrating an initial model of the acid−base chemistry. However, in the second group, the number of students who had grasped the connection of the mathematics to the model was much higher (29%).

### Inquiry Lab Assessment

The students continued to develop their understanding of acid−base chemistry with a guided inquiry lab and an inquiry lab. These laboratories required students to articulate the process for solving the problem using chemistry. These two laboratories both required greater student input leading to development of student models of acid−base chemistry or refinement of an existing student model. The guided inquiry laboratory was a real-time laboratory, whereas the open-ended inquiry was a virtual lab. The advantage of the virtual laboratory format is that it can allow an open-ended inquiry lab without opening any safety concerns about the consequences of student choice in laboratory design. The challenge of this lab is that students must have enough understanding of the previous laboratories and concepts to successfully design a working titration of an unknown weak acid.

To assess the students' development of acid−base models and their understanding of the chemistry, the students were asked to do a titration (similar to the first assessment question) and explain the results of their titration. The second part of this assessment was to discern if the student understood the relationship between the ions in solution, the mathematical relationship and the skills required by the lab.

### Assessment Comparison

Students responses on the two assessments were ranked into three categories: highly proficient, proficient, and below proficient. For the first assessment, the student responses that only described the lab process were ranked as below proficient. Student responses that only gave the math were ranked as proficient, whereas students who connected the math to the lab process were ranked as highly proficient. Student responses were coded independently by two evaluators, and the rankings were compared. Ranking discrepancies occurred in less than 5% of the students in the two groups.

### Summative Assessment

These rankings were compared to the scores on the formative assessment that were ranked into the three levels. The unit test had 36 questions that tested understanding of the Arrehenius model, the Brønsted−Lowry model and the process of titrating an unknown acid to obtain the concentration (Supporting Information). A score of 80% was categorized as highly proficient and a score of 60% was categorized as proficient. A score of 50% and lower was considered below proficient. To reach a proficient score a student was expected to have a clear understanding of both acid−base models as well as the laboratory process.

For the first group of students who were exposed to the virtual laboratories without the additional discussion relating the virtual lab to models, the improvement from a below-proficient score was 29% (Table 3) and the improvement from proficient to highly proficient was 22%. In the second group, a


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higher number of students ranked at the proficient level; however, there was also a higher level of improvement in that 78% of the students raised their scores from below proficient or proficient to the next higher level. This finding supports the importance of incorporating the acid–base models into data discussions so that students develop a stronger understanding of acid–base chemistry.

### Student Perceptions in Survey

In the student survey, the students in both groups found that virtual laboratories increased their confidence in real-time laboratories (85.2%) and also improved their understanding of real-time laboratories (90%). Students also found virtual laboratories easier to perform (89%), easier to understand (71.9%), less intimidating (73.8%), and easier to fix or correct a mistake (93.8%). When asked specifically about setting up a titration and using a buret, 80.9% students felt it was easier in a virtual lab. When the prompt asked students if they understood how to do a titration, 86.6% students felt they understood it with an acid of unknown concentration, whereas 81.9% understood when it was with a base of unknown concentration.

Students were asked to rank their experiences in the class that involved traditional instructional methods as well as technology-based instructional methods. Students ranked the virtual laboratories as most helpful out of all instructional methods (28%). Students ranked real-time laboratories as the most fun of all instructional methods (36%). When students were asked to elaborate about technology in this chemistry class, the majority of students surveyed described the technology being helpful (77%), whereas only a small minority of the students (10%) felt it made no difference. In further analysis of this result, the students who did not find the technology helpful represented a small percentage of the students who struggled with understanding the content in the laboratories, both real-time and virtual laboratories. The majority of students found technology helpful and stated that it made the other laboratories more understandable. The virtual laboratories produced higher student confidence about the chemistry content in actual laboratories. In addition, 79% of all students showed improvement in assessment scores following the inquiry laboratories.

## ■ CONCLUDING COMMENTS

The implications of this study are that technology, specifically virtual laboratories, can improve the perceived understanding of chemistry of most students (77%). The use of virtual laboratories provides the needed safety supports to present an inquiry laboratory with acid–base chemistry. Furthermore, the incorporation of the virtual laboratory lowered students' affective filter about chemistry, resulting in higher confidence levels about the content that then led to better assessment scores.

The students, who received the additional instruction through a discussion of data with acid–base model comprehension as a goal, gained a stronger overall understanding of the acid–base models and of the chemistry on an atomic level. The success of this pedagogic approach was supported by a greater level of improvement from lower comprehension of acid–base models in the formative to the higher levels of comprehension in the summative assessment.

The instructional approach of inquiry laboratories promotes critical thinking skills as well as lab design skills. The use of open inquiry is the most challenging for students and at same time the best test of students' critical thinking skills. The transition to open inquiry is best supported through a gradual progression of increasing inquiry in laboratories that work with the same laboratory skill (in this study, titration). The transition toward open inquiry is best supported through formative assessment of the students' understanding so that the students are able to successfully design the laboratory in the open-inquiry lab. The addition of teacher-led discussions of the data in connection to the different acid–base models helped students have a stronger grasp of the chemistry on the atomic level as well as greater understanding of the purpose of the laboratory exercise. This study illustrates that incorporating technology into the curricular design of a unit with the support of the data discussions resulted in the greatest gains for students' understanding of acid–base chemistry.

## ■ ASSOCIATED CONTENT

### Ⓢ Supporting Information

Description of two laboratories; assessment sample questions from the formative and summative assessment. This material is available via the Internet at http://pubs.acs.org.

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### Notes

The authors declare no competing financial interest.

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