Using a Systems Thinking Approach and a Scratch Computer Program To Improve Students’ Understanding of the Brønsted–Lowry Acid–Base Model

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ABSTRACT: Numerous previous studies have reported the difficulties associated with learning the Brønsted–Lowry acid–base model. The Brønsted–Lowry acid–base model requires complex systems thinking because it considers random interactions between reactant and product particles and effective particle collisions in forward and reverse reactions. The system elements are dynamic, complex, and mutually independent. Furthermore, phenomena constantly change and interconnect with all elements of the system. Despite these difficulties, previous studies, thus far, have not reported methods that can effectively teach students the Brønsted–Lowry acid–base models, which require systems thinking. To solve this problem, we must understand the ontological attributes of science concepts, such as the Brønsted–Lowry acid–base model. In this study, we propose a Scratch program to help students understand the Brønsted–Lowry acid–base model.

KEYWORDS: High School/Introductory Chemistry, Computer-Based Learning, Acids/Bases, Systems Thinking

INTRODUCTION

Recently, science education has emphasized the teaching of scientific models.1–3 A scientific model is not a natural phenomenon but, rather, the representation of the “idea” of that natural phenomenon. One natural phenomenon can be explained in several ways depending on the specific idea or point of view of the scientist who has developed a specific model.4,5

Therefore, scientists have produced different scientific models for the same natural phenomena, and the nature of this scientific activity is related to model diversity. For example, the Arrhenius and Brønsted–Lowry acid–base models are two representative explanations of the acid–base reaction phenomenon. These two models were created by different scientists, and because the models are mutually exclusive, we must understand the attributes of each model separately.6

In most textbooks, however, the Brønsted–Lowry acid–base model uses broader explanations for the acid and base reaction phenomenon than the Arrhenius acid–base model. Furthermore, most textbooks include the Arrhenius acid–base model within the Brønsted–Lowry acid–base model.7–14 Therefore, students perceive that the two models have an inclusive relationship, and they tend not to pay attention to differences in the properties of these models. This makes understanding the characteristics of each model difficult for students.15–17 Numerous studies have reported that students find it difficult to understand the Brønsted–Lowry acid–base model after learning the Arrhenius acid–base model.18–24 In particular, it is worth noting that students who are educated with different methods that vary by country face similar obstacles when attempting to learn the Brønsted–Lowry acid–base model.

Issues with learning the Brønsted–Lowry acid–base model are related to the properties of the Brønsted–Lowry acid–base model. The Brønsted–Lowry acid–base model requires reversible thinking that takes into account not only forward reactions but also reverse reactions.6,25 Understanding of the Brønsted–Lowry acid–base model requires the ability to contemplate reaction kinetics, because forward reactant reactions, reverse product reactions, and continuous complex reactions among the reactants and products require simulta-
neous consideration. Chemical reactions due to particle collisions require probabilistic thinking, such as the idea of effective collision, and such probabilistic thinking must consider countless particles. In addition, only the dominant reaction appears to proceed, despite the competition between forward and reverse reactions during a probabilistic effective collision. Understanding the dominant reaction and the various reactions that actually occur ultimately leads to an understanding of chemical equilibrium.26

Ultimately, understanding the Brønsted–Lowry acid–base model requires systems thinking, which is a comprehensive idea of the reactions. Numerous studies have reported difficulties in learning the Brønsted–Lowry acid–base model, but thus far, there are no solutions to this problem because these studies have failed to develop effective learning materials for students to create the systems thinking skills that are required to understand the model. Therefore, the purpose of this study is to develop learning materials to help students understand systems thinking with respect to the Brønsted–Lowry acid–base model, which requires the concept of chemical equilibrium from a complex reactions perspective. To visually understand the properties of the Brønsted–Lowry model, we used the Scratch program developed by the MIT Media Lab, which has a relatively low coding barrier among the many existing programming tools. Because the Scratch program is a form of block coding, it has the advantage that it can be easily understood even by nonexperts because it is intuitive and simple to use compared with other coding programs. Because it is a web-based program, there is no need to install a separate program; therefore, it can be easily used in schools. In addition, the Scratch program is open-source, which emphasizes sharing and collaboration. Therefore, many studies related to coding education have used the Scratch program as an effective tool.27−31

## OVERVIEW OF THE BRØNSTED–LOWRY ACID–BASE MODEL

### Ontological Characteristics

Chemical equilibrium is one of the most important concepts in chemistry and is a necessary concept in understanding acid–base, redox, and dissolution reactions.32 However, numerous previous studies have consistently reported on the many obstacles faced by students in understanding chemical equilibrium.33−39 The reason why certain scientific concepts, such as chemical equilibrium, are more difficult to learn than other scientific concepts can be explained by the ontological category of the scientific concept.40−42 Figure 1 shows the ontological categories of science concepts. The science concepts are divided into matter and process views.43 The process view is divided into sequential and emergent processes. Chemical equilibrium belongs to an emergent process category in the process view.

The matter view is the idea that matter properties come from the material, whereas the process view is the idea that matter properties originate from the relation between the material and the surrounding environment. For example, the Arrhenius acid−base model belongs to the matter view because it focuses on the presence of hydrogen ions or hydroxide ions in materials when classifying acids or bases.4 Acid and bases are judged by considering the dissociation of H+ or OH− in materials when the materials dissolve in water. Conversely, the Brønsted–Lowry acid−base model classifies acids and bases by considering the situation in which one substance meets another. For example, when CH3COOH reacts with H2O, H2O is relatively more basic than CH3COOH (Ka,acetic-acid > Kwater). Therefore, H2O is classified as a base. However, when H2O reacts with NH3, H2O is classified as an acid. The Brønsted–Lowry acid−base model is a process view because classifying materials as an acid or a base always depends on the reactant materials.

Table 1 summarizes sequential and emergent processes in the process view.16 Sequential processes involve only a single direction for the interactions among elements. Understanding only one component of the interactions among the elements can, therefore, render the entire system understandable. However, the emergent process contains different directions for the various interactions among the elements, and these interactions occur simultaneously. Therefore, a partial understanding of the interactions among elements does not lead to an understanding of the entire system in the emergent process. We must consider collective summing or the net effect of all interactions. The Brønsted–Lowry acid−base model belongs to the emergent process category because it simultaneously considers the reactions between acids and bases in the forward reaction and the conjugated acid and base reactions in the reverse reaction, as well as the various materials that randomly interact with each other. However, when the acid−base reaction between CH3COOH and H2O is expressed as CH3COOH + H2O ⇄ CH3COO− + H3O+, it is easy to misunderstand the reaction as a sequential process in which all of the reactants proceed in the forward reaction, and all of the products then proceed in the reverse reaction.

### Brønsted–Lowry Acid–Base Model as Chemical Equilibrium

Chiu et al.26 argued that students have difficulty learning chemical equilibrium because there is no mental model that simultaneously considers complex interactions between many particles in the microscopic world. For example, changing from the viewpoint that the reaction has stopped when chemical equilibrium occurs to the viewpoint that the reaction is still happening after reaching chemical equilibrium is not an easy

![Figure 1. Ontological categories of science concepts. The data are from refs 41−43.](image-url)
ment. Another study reported that students tend to understand chemical equilibrium as a system where the reaction only occurs in one direction, rather than as a system in which both the forward and reverse reactions occur simultaneously. In Banerjee’s study, students still had misconceptions related to equilibrium after learning. Banerjee insisted that this result is characteristic not only of the participants of the study but of general students. When chemistry teachers introduce Le Chatelier’s principle to teach students about the direction of chemical equilibrium movement in reactions, most students are unable to understand why Le Chatelier’s principle occurs in the reactions, because they do not understand chemical equilibrium.

To understand the direction of chemical equilibrium movement, students must first understand the concept of the reaction rate. Students can predict the direction of equilibrium movement by comparing the forward and reverse reaction rates. To understand chemical equilibrium by introducing the reaction rate concept, we must consider not only the concentration and temperature of the reaction but also probabilistic thinking related to the effective collision of a countless number of particles. In many chemistry textbooks, however, the Brønsted–Lowry acid–base model is introduced in the chapter on chemical equilibrium without an introduction of the reaction rate concept. These problems make it difficult for students to understand the Brønsted–Lowry acid–base model.

### DEVELOPMENT OF CODING FOR SYSTEMS THINKING

#### Understanding of Systems Thinking

The term “systems thinking” was first mentioned by Barry Richmond in 1987. The main characteristic of systems thinking is the ability to look at the entire system and not the individual elements of that system. To understand the problems that may arise in a system, we must consider the entire system, not just several elements of that system. Systems are dynamic, complex, and mutually dependent and it is important to recognize that phenomena always change constantly and are interconnected with all aspects of the system.

Systems thinking comprises understanding the elements that make up a system and the relationships among those elements. System thinking has three main characteristics. First, systems thinking involves a feedback loop structure, which focuses on continuous formation of a relationship between elements rather than the characteristics of each element in the system. Second, systems thinking focuses on comprehensive thinking (i.e., the system is not a simple sum of elements). All properties of the system are expressed through the relationships among the elements. Third, dominant feedback exists among various feedbacks. Various feedbacks exist in the system, but there are specific feedbacks that determine the overall characteristics of the system. These dominant feedbacks shift to different feedbacks depending on the conditions.

Figure 2 shows relationships among elements in systems. Figure 2a shows a one-sided, cause and effect relationship among elements, which is in the ontological category “sequential process”. Figure 2b shows a multidirectional relationship among elements that leads to a dynamic system of continuous interactions and thus is an “emergent process”.

However, in most chemistry textbooks, the Brønsted–Lowry acid–base model is presented as a generic chemical reaction formula, such as \( HA + HB \rightleftharpoons H_2A^+ + B^- \). These chemical reactions are expressed by only the smallest numbers of particles, making it difficult to contemplate the relationships among cyclic feedbacks. In particular, reactions that involve weak acids and bases must express the concept of effective collisions at dynamic equilibrium. This concept, however, is not expressed in the chemical reaction equations. Systems thinking is difficult for students to learn through observations in chemical laboratories. On the basis of chemical experiments that deal with matter, students tend to understand acid and base reactions in a matter view. The ball-and-stick model (Figure 3), which is the most popular model for expressing chemical reactions, is unable to express the motions of countless microscopic particles that occur simultaneously.

### Algorithm for Coding the Brønsted–Lowry Acid–Base Model

Coding refers to the use of a certain programming language to recognize a problem, analyze it, and develop it as a stepwise
algorithmic procedure to represent a model. Coding teaching strategies are used to help students understand complex phenomena or concepts. In general, students face difficulties when attempting to understand a system that contains various interactions among elements using only textbooks and figures. However, using computers to express the complex relationship among elements as an algorithm enables students to understand the entire system visually.27−31 During the course of expressing the scientific model with coding, students decompose complex model properties and parallelize the relationships among elements. This parallelized coding is automatically imaged and can be used to verify that the model is correct. In particular, we can understand the entire system by visually implementing the simultaneous movement of numerous particles. The Next Generation Science Standards, which were developed in 2013 by the National Science Teachers Association, the American Association for the Advancement of Science, the National Research Council, Achieve, a nonprofit organization, and a consortium of 26 states, emphasizes the “practice” of computational thinking.3

The coding developed in this study is a chemical reaction between H2O and CH3COOH. The chemical equilibrium in this reaction is related to the acid equilibrium constant of CH3COOH. The coding algorithm for equilibrium constants related to the dissociation of CH3COOH is shown in Figure 4.

![Figure 3. Representation of a chemical reaction using the ball-and-stick model.](image)

![Figure 4. Algorithm for coding developed in this study, i.e., the H2O + CH3COOH ⇄ H3O+ + CH3COO− reaction.](image)
In the first step, the forward reaction rate constant (i.e., the probability of reaction occurrence) and the reverse reaction rate constant for the dissociation of H⁺ in CH₃COOH molecules take inputs from 0 to 100. In this case, students can explore how the chemical equilibrium shifts through randomly entered rate constants, such as if the rate of the forward reaction is higher than the rate of the reverse reaction, or vice versa. This step verifies the model using the code. Visual confirmation that the expression in the entire system varies depending on the constant entered is critical. In the next step, the four chemical species in this reaction are represented as variables (i.e., w, x, y, and z). There are various collision situations that exchange protons but, in this study, the collision situation for proton movement is simplified into two cases. In addition, if there is no effective collision, protons do not move between the chemical species. For this purpose, the rate constant entered into the collision situation determines proton movement, which is a probabilistic view.

**Coding**

The coding presented herein is developed by the researchers to represent the Brønsted–Lowry model. The coding can be diverse even if the same result is obtained. Therefore, the following coding is one of the examples.

The relationships among elements are the most important aspect of systems thinking. In the Scratch program, an element corresponds to a “sprite”. In Figure 5, we set up two chemical species (water with hydronium ion and acetic acid with acetic ion) in one sprite. In addition to the sprites associated with the elements present in the system, there is another sprite. This sprite manages variables for the forward and reverse reaction rate constants and represents the number of particles when multiple particles react simultaneously. This sprite does not appear on the screen.

Figures 6 and 7 show the codes for each sprite. The initial forward and reverse reaction rate constants for the button sprite are set to 50. In this system, the equilibrium constant is 1. However, students can adjust the speed to between 0 and 100 by scrolling the mouse on the computer screen. The initial shapes of the H₂O and CH₃COOH sprites are set to w and x, and the scenario is set to dissolve CH₃COOH in H₂O. As shown in Box 1 of Figures 6 and 7, the particles were set to move randomly. The outlines that exist in all of the particle sprites are black. Thus, the coding of “if touching color black” in Figure 6, Box 1 indicates that the particles bounce off each other when they collide. As shown in Box 3 in Figure 6, a reaction occurs when w and x or y and z meet. This reaction does not always occur, but the already input forward or reverse reaction rate constant (occurrence probability) determines the reaction progress. If a forward reaction occurs, the code broadcasts to the sprites that a forward reaction has occurred. In contrast, if a reverse reaction progresses, the code broadcasts that a reverse reaction has occurred in each sprite. This coding represents the relationships among the elements. The relationships appear depending on the input rate constant values, resulting in either the forward or reverse reaction acting as the dominant feedback. In the code, when each sprite receives a broadcast for a forward or reverse reaction (Box 2 in Figures 6 and 7), each sprite changes its shape into a conjugate acid or conjugate base, which changes the variable values accordingly.

This alone does not encompass systems thinking for the Brønsted–Lowry acid–base model because this simulation represents the reaction between only one H₂O particle and one CH₃COOH particle. To represent simultaneous interactions among multiple particles, we must increase the number of particles in the code. This represents the addition of the iteration function shown in Figure 6 via code parallelization. A part of this code is shown in Figure 8.

Students are able to understand how the system changes on the basis of the computer screen display, which is a result of the code that allows multiple particles to interact simultaneously. The sprite for CH₃COOH probabilistically interacts with 10 H₂O particles, and the resulting interaction affects the H₂O particles. In addition, the code shown in Figure 9 was added to express the concentration of CH₃COOH (i.e., the number of CH₃COOH particles) so that the rate constant input into the system can confirm systems thinking (i.e., chemical equilibrium). Figure 10 shows a scenario of the Scratch implementation.

The Scratch coding presented above is an example that can work for a novice. Using this example, one can easily understand the Brønsted–Lowry acid–base model. However, this coding has a vast amount of repeated code. Concise coding may make it difficult for novice to link emergent scientific models; however, we suggest more concise coding for readers of higher levels. In the proposed coding for high-level readers, “create clone of sprite” creates multiple particles instead of a vast amount of repeated code. Figure 11 shows the code for calculating the number of particles of acetic acid. The simplicity of this code can be compared with that in Figure 9. However, students need to understand “making variables and lists” and “my block” for coding.

**Guidelines for Teaching**

The teaching materials developed in this study can be used for students to observe the emergent process visually to overcome the their limitations with complex systems thinking. However, merely observing the emergent process may limit systems thinking regarding the underlying mechanism. Therefore, it is recommended that students self-code to understand more fundamental mechanisms.

We conducted a class to teach the Brønsted–Lowry acid–base model for 18 students in 11th grade. The students’ familiarity with the Scratch program varied. Therefore, we divided the coding process into five steps. Only the sprites of water molecule and the acetic acid molecule were presented to the students. In Step 1, the students were asked to implement Scratch so that a water molecule and acetic acid molecule did not react with each other but moved randomly. In Step 2, the students were asked to implement Scratch to transfer a hydrogen particle from the acetic acid molecule to the water molecule when the water and acetic acid molecules met by...
moving. Also in Step 2, the students were asked to implement Scratch so that a hydrogen particle from an acetic acid molecule transferred to a water molecule when the water and acetic acid molecules met because of their movement. In Step

Figure 6. Code of the acetic acid sprite for the Brønsted—Lowry acid—base model.

Figure 7. Code of the water sprite for the Brønsted—Lowry acid—base model.
3, the students were asked to use Scratch to add a hydrogen particle transfer process to Step 2 when a water molecule that had obtained a hydrogen particle met an acetic acid molecule that had lost a hydrogen particle. This implementation involved the concept of equilibrium. Step 4 was similar to Step 3, but the students used 10 water and acetic acid molecules each. All the students participating in the class did not find coding from Step 1 to Step 4 difficult, despite their different abilities in operating the Scratch program. In the final step (Step 5), students were asked to implement the probability ($k$) of transferring hydrogen particles from 10 acetic acid molecules to 10 water molecules and the probability ($k'$) of transferring hydrogen particles from water molecules that had received hydrogen particles to acetic acid molecules that had lost hydrogen particles. The researchers guided the students to recognize that the situation in Step 4 occurred
when the probability was set to 100 in Step 5. They also explained to the students that the probability values of strong acids are 100, and those of weak acids are less than 100. Through Steps 4 and 5, the students were able to determine acid strength by linking it with the probability of hydrogen particles being transferred.

We also asked the students to observe the system changes when they coded different $k$ and $k'$ values in Step 5. Through the coding process, they understood the relationship between reaction equilibrium and forward and reverse reactions. Some of the students had difficulty in implementing probability when coding, but other students with good Scratch skills succeeded. As Scratch allows sharing of scripts, the students overcame the difficulty of forming the concept of probability by watching successful scripts. The time taken by 18 students to perform Steps 1–5 was about 100 min.

Steps 4 and 5 are oversimplified situations. In an aqueous solution, there should be many more water sprites than acetic acid sprites in both the initial stage and at equilibrium; however, creating a large number of sprites is hectic for the students. The students who practiced in simplified situations are able to implement the Scratch program that represents a natural situation in that the number of water molecules is greater than the number of acetic acid molecules, as in an aqueous solution.

**Evaluation Effect**

We examined the coding effects on 56 students in the 12th grade in Korea. We explained the purpose of this study and received consent from the students. The participants were already familiar with the Brønsted–Lowry acid–base model, as they had studied it in their chemistry class as part of their regular school curriculum. These students practiced the coding developed herein for 100 min. Four items related to the acid–base model were given to the students before and after the coding practice to confirm the educational effect. Table 2 shows the questionnaire for estimating students’ understanding of the acid–base model.

Each item was scored from 1 to 4 points on the basis of the study by Lin and Chiu. The results are shown in Table 3. In Item 1, which was related to ionization of a strong acid, no significant difference was observed in the pre- and post-tests. Therefore, the effect size of this item was not calculated. In Item 2, which was related to ionization of a weak acid, statistically significant differences were observed in the pre- and post-tests ($p < 0.05$), and the effect size was 0.71. In Item 3, related to hydrolysis of a salt, there were statistically significant differences ($p < 0.05$), and the effect size was moderate (Cohen’s $d = 0.43$). Item 4, related to the leveling effect, was the most difficult for the students. There was statistically significant difference ($p < 0.00$), and Item 4 showed the largest effect size (Cohen’s $d = 1.09$). These results showed that the coding practice developed herein does not display educational effects in simple contexts, such as in the ionization of strong acids. However, educational effects are seen in complex contexts, such as weak acid ionization, salt hydrolysis, and leveling effect. In other words, students developed a deeper understanding by considering various interactions via systems thinking through coding. This study comprised a one-group pretest–post-test design, which may result in slightly excessive effect sizes and threats to maturity, history, and test effect. Nonetheless, the effect sizes of the three items in this study were more than moderate, and these results could be interpreted as educational effects.
CONCLUSIONS AND IMPLICATIONS

The code developed in this study can help students to visually confirm both the initial state of CH₃COOH in water and the state of the subsequent chemical equilibrium; this process enables students to understand that multiple particles interact simultaneously. In this study, we started with 10 reactant particles, but students can confirm the dynamic change in equilibrium by adjusting the numbers of CH₃COOH and H₂O particles, which visually represent material concentrations. The new teaching method proposed in this study is different from those in other studies and allows students to observe particle motion solely on the computer screen.

In this study, codes were developed by restricting the interactions to four chemical species. However, if teachers and students succeed in implementing the Brønsted-Lowry acid-base model using this coding, the creation of more complex systems thinking scenarios is certainly possible. For example, in a situation where three substances, such as H₂O, CH₃COOH, and HCl, meet simultaneously, we can construct a systems thinking model that considers the various interactions among these substances. Teaching methods that provide students tools that can lead to systems thinking are the methods that are most likely to help students understand modeling. Without these thinking tools, it is hard to escape from using traditional chemistry teaching methods, which simplify students’ ability to think and solve problems related to chemical reactions under limited conditions. Until now, we had maintained traditional chemistry teaching methods, which reduced the burden of students’ learning of complex natural phenomena. This study not only allows students to understand and practice complex systems thinking, such as in the Brønsted-Lowry acid-base model, but also gives them the opportunity to create new models.

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Notes

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