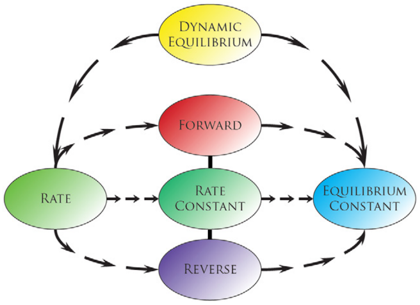
A Kinesthetic and Collaborative Activity to Improve Conceptual Understanding of Chemical Equilibrium

Roshini Ramachandran[1*], J. Rachel Prado[2], and Joe L. March[3]

[1]Department of Biology and Chemistry, California State University, Monterey Bay

[2]Department of Chemistry and Biochemistry, Auburn University

[3]Department of Chemistry, University of Alabama at Birmingham



Abstract

While teaching in large lecture halls, it is challenging even for experienced teachers to hold their students' attention for the entire class period. Owing to the large enrollment in STEM introductory courses, it is especially crucial to incorporate active-learning strategies that enhance student engagement. We have developed a kinesthetic student activity to demonstrate the dynamic nature of chemical equilibrium in a large classroom setting. The activity consists of two parts; the first employs a demonstration utilizing student volunteers participating in a reversible chemical reaction while the second part involves students working in small groups using objects to track the movement of "molecules" for different reversible reactions. The primary learning objectives of the activity are to (i) perform the movement of molecules during chemical equilibrium, (ii) explain the dynamic nature of equilibrium, and (iii) connect the concepts of rate constants and equilibrium constant. This activity has been implemented in a large classroom of 100+ students who were life science majors, with student feedback stating that the activity enhanced their understanding of chemical equilibrium. Pre-activity and post-activity quiz performance were an indicator that learning gains were observed. This report provides a comprehensive set of resources for chemistry faculty to use while implementing this activity in their classroom.

Primary Image: This activity has the potential to aid in addressing common misconceptions about the dynamic nature of chemical equilibrium. It also serves as a useful tool to create connections between chemical equilibrium and reaction kinetics.

Citation: Ramachandran R, Prado JR, March JL. 2024. A Kinesthetic and Collaborative Activity to Improve Conceptual Understanding of Chemical Equilibrium. CourseSouce 11. https://doi.org/10.24918/cs.2024.29

Editor: Ellis Bell, University of San Diego

Received: 9/7/2023; **Accepted:** 8/6/2024; **Published:** 9/4/2024

Conflict of Interest and Funding Statement: None of the authors have a financial, personal, or professional conflict of interest related to this work.

*__Correspondence to:__ rramachandran@csumb.edu

Learning Goals

Students will:

- ◊ understand the concept of a dynamic equilibrium.
- ◊ recognize that equilibrium represents a constant state of opposing forward and reverse reactions.
- ◊ visualize the dynamic nature of equilibrium.
- ◊ analyze the connection between reaction rates and the equilibrium constant (K_{eq}).
- ◊ From the Science Process Skills Learning Framework:
  - » Use basic mathematics (e.g., algebra, probability, unit conversion) in biological contexts
  - » Work productively in teams with people who have diverse backgrounds, skill sets, and perspective

Learning Objectives

Students will be able to:

- ◊ perform the movement of molecules during chemical equilibrium.
- ◊ explain the dynamic nature of equilibrium.
- ◊ connect the concepts of rate constants and equilibrium constant.
- ◊ explain how chemical equilibrium differs from an irreversible reaction.
- ◊ calculate rate and equilibrium constant using given concentration and rate constant data.
- ◊ predict changes to equilibrium when the forward and reverse rate constants are altered.

INTRODUCTION

While teaching in large lecture halls, it is challenging even for experienced teachers to hold their students' attention for the entire class period (1). Owing to the large enrollment in STEM introductory courses, it is especially important to incorporate active-learning strategies that enhance student engagement. There is a need for teaching strategies that provide content in a way that aids in retaining the knowledge, as well as creating connections between previous and current knowledge, which is vital for students to evolve from novices to experts in the subject area (2). Active-learning strategies have shown to be effective in explaining abstract concepts taught in STEM courses (3), such as utilizing clickers, think-pair-shares, and case-study worksheets (4–6). Student-centered strategies that include group activities in large-lecture classes have supported learning for life science/health majors (7–9). This article details an adapted in-classroom activity involving collaborative groups of students to enhance conceptual understanding of the dynamic nature of chemical equilibrium. Equilibrium is an apt topic for active learning as the concept is abstract, complex, and is often susceptible to misconceptions (10–12). Knowledge of chemical equilibrium is widely considered as a foundational topic required for all biology and biochemistry majors (13, 14). Therefore, the target audience for this demonstration is undergraduate life science majors, who would benefit from having a visually tangible component to theoretical chemistry content.

Thus far, classroom demonstrations on equilibrium topics have focused on performing relevant experiments on a small scale to provide a visual component to the topic. These employ chemical reactions that have visual (15–19), sensory (20), or phase (21) changes, and hence require a designated space, laboratory glassware, and PPE. Such demonstrations are useful in linking lecture concepts to laboratory experiments and in cultivating application-based learning (22, 23). However, they do not provide a tangible link from abstract concept to working knowledge, which is where students mostly have trouble learning (11, 23). It is a common student misconception that chemical reactions come to a standstill when equilibrium is reached. In order to address this issue before it transfers into future lecture and laboratory courses, it is essential to illustrate the dynamic nature of equilibrium to students. Hands-on instructional approaches have utilized dice (24), playing cards (25), games (26), or diagrams (27) for students to view the progress of reactions toward equilibrium; these have been applied for smaller class sizes. Other reports of in-class activities implemented forty matches or fifty coins as "molecules" in an equilibrium experiment (28, 29). These reports have served as inspiration for our activity; however, we have re-formulated the activity using far fewer number of objects to avoid confusion. Our activity comprises two parts to promote active learning in a large classroom. The first part involves a student-centered demonstration of student volunteers acting as "molecules" in a reversible chemical reaction moving between reactants and products. For this part, the students individually process the information provided through the demonstration. The second part of the demonstration focuses on the students collaborating in small groups to repeat the demonstration for different reaction parameters using small objects like candies or buttons. This activity has been implemented in large classrooms of 100+ students and we have obtained student feedback on the effectiveness of the activity. Supporting learning materials such as in-class worksheets, pre-activity and post-activity quizzes are provided in this report, as well as feedback from a post-activity student survey. The goal of this report is to create a set of resources that faculty across all institutions can utilize to provide for easy facilitation of this dynamic equilibrium demonstration in their classroom. Additionally, this activity provides an opportunity for students to tie together the concept of equilibrium with the concept of reaction rate by prompting a discussion linking the numerical values of the rate constants to the equilibrium constant using the following equations:

***Eq. 1*: Rate = *k* [*reactant*]**
***Eq. 2*: K_{eq} = [*products*]/[*reactants*]**
***Eq. 3*: $K_{eq} = k_f / k_r$**

where K_{eq} is the equilibrium constant, [*reactants*] is the concentration of reactants, [*products*] is the concentration of the products, and *k* is the rate constants with the subscript *f* or *r* representing forward or reverse reaction respectively.

It is important to note that this activity focuses on a reaction with a 1:1 stoichiometry. This simplifies the system and allows for a straightforward application of the Law of Mass Action, where the exponents in the equilibrium constant expression become 1.

Misconceptions Addressed

a. A reversible chemical reaction comes to a standstill once equilibrium is reached *i.e.,* no more reactants are forming products and vice versa.
b. In a reversible chemical reaction, the forward and backward reactions do not occur simultaneously.
c. At equilibrium, the concentration of reactants equals the concentration of the products.
d. The rate constant of the forward reaction is equal to the rate constant of the backward reaction for all reversible reactions.

Intended Audience

This activity is suitable for undergraduate students taking an introductory chemistry course such as general chemistry or fundamental chemistry. We utilized this activity in a first-year general chemistry course for life science majors. The teaching setup was in a large lecture hall comprising 100+ undergraduate students. Chemical equilibrium is typically taught in a first-semester or second-semester general chemistry course, making this activity suitable for either. Students in this course completed an introductory chemistry course, however, the topic of chemical equilibrium was not covered prior to this course. AP chemistry or high school chemistry is not a pre-requisite for students in this course. We recommend using this activity at the beginning of teaching chemical equilibrium (either in the first or second lecture) so that students are introduced to the concept of dynamic equilibrium early on.

Required Learning Time

This lesson has been designed for a 1-hour class, and we have provided a Teaching Timeline in Table 1.

Prerequisite Student Knowledge

Knowledge of basic chemical reactions, reaction rates, and the concept of reversible reactions is essential. Familiarity with the Law of Mass Action and stoichiometry will be advantageous and are typically covered in units prior to this topic.

Prerequisite Teacher Knowledge

A solid foundation in chemical reactions, including reactants, products, and the concept of reaction rates, is required. The teacher should be familiar with how factors like concentration and temperature can influence reaction rates. A clear grasp of the concept of dynamic equilibrium—such as knowing that at equilibrium, the rates of the forward and reverse reactions are equal—is essential for this activity. Familiarity with the Law of Mass Action is helpful, especially for interpreting the relationship between concentration and equilibrium constants (*Eq. 1–3*). Basic knowledge of stoichiometry, particularly the concept of 1:1 ratio between reactants and products, is beneficial as the activity demonstrates equilibrium in a simple system. We recommend this open-source textbook for background reading (OpenStax Chemistry 2e, Chapter 13).

SCIENTIFIC TEACHING THEMES

Active Learning

This lesson utilizes collaborative learning through a small groups activity (1, 5) and hands-on learning (24–29) for students to be actively involved in discussing calculations, predicting movements, and recording data. It also engages students kinesthetically through movement (31) during the small groups activity. Throughout the activity, the instructor facilitates discussions, guiding students to record data, interpret observations, and connect them to concepts learned in class.

Assessment

We administered pre-activity and post-activity multiple-choice quizzes to determine the impact of this activity on achieving the targeted student learning objectives. Learning gains (23) were measured through analyzing student responses to the pre-/post-quizzes. Students completed the pre-activity quiz in class immediately before the activity, and the post-activity quiz was done by students immediately after the activity and small groups discussion.

Inclusive Teaching

This lesson activity strives to be inclusive and acknowledge the value of different approaches to learning in the science classroom. It uses multiple representations of the concept (physical movement, calculations, and discussions) to engage students who may prefer visual (28, 29) or kinesthetic means (31). The group work which involves discussion in small groups and going through the worksheet process in Part II allows students to learn from each other's perspectives and approaches (4, 5). This can foster a sense of community in the classroom. Students who struggle with making abstract concepts tangible could benefit from a more hands-on approach instead of just recording data as with typical equilibrium calculations (10–12).

For students with mobility limitations, alternative ways to participate have been offered in the article. They could track the movement of molecules on a worksheet or use a virtual method of participation (30). The key is to ensure all students feel included and have a chance to engage with the core concepts.

LESSON PLAN

Overview of Activity

The first component of the equilibrium activity involves student volunteers acting as 'molecules' in a reversible chemical reaction comprising a forward and reverse reaction. For this part, the students individually process the information provided using worksheets to track their progress. All volunteers will begin as reactants and after being given the forward rate constant, students calculate the rate of the forward reaction or the number of students becoming products (*Eq. 1*). The instructor then introduces the reverse reaction and reverse rate constant for students to calculate the reverse rate and move from products to reactants (*Eq. 1*). The forward and reverse reactions continue with student volunteers moving back and forth until equilibrium is reached. The second part of the demonstration focuses on the students working in small groups to repeat the demonstration for different reaction parameters using small objects like candies or buttons.

Part I: Volunteer Demonstration

We performed this demonstration with 12 students as shown in Figure 1. Step by step instructions for the demo completed with 12 students are as follows:

- The demo begins with the instructor asking for twelve volunteers to be "molecules" with everyone on the reactant side as shown in Figure 1. The students are asked to stand in front of the class.
- Students in the audience are handed worksheets (Figure 2) to keep track of volunteer positions as reactant or product.
- The forward reaction is provided a rate constant of ½; students (volunteers and audience members) are given the opportunity to determine how many volunteers should move to the product side.
- Students proceed by calculating the 'rate' of the forward reaction using *Eq.1* and reach the conclusion that the number of students moving to products is six, which is one-half of twelve or the number of students times the rate constant. Volunteers move when the instructor says "react," and the audience records how many volunteers are now in reactant (6) and product (6) sides.
- Students are given the reverse rate constant of ¼, while being reminded that the forward reaction is still taking place. Students now calculate the 'rate' of the reverse reaction using *Eq. 1* and arrive at the conclusion that one-fourth of six is one and a half; the instructor steps in to interject that it is necessary to round up whenever there is a fraction. In the second iteration of the reaction, half of six volunteers move to the products, while two volunteers on the product side move to the reactant side. The audience records the new position of reactants (5) and products (7).
- For the third iteration, students discuss how many should move to products or reactants with the new concentration and move across when the instructor says react. The audience records the position of reactants (4) and products (8), which is now at equilibrium.

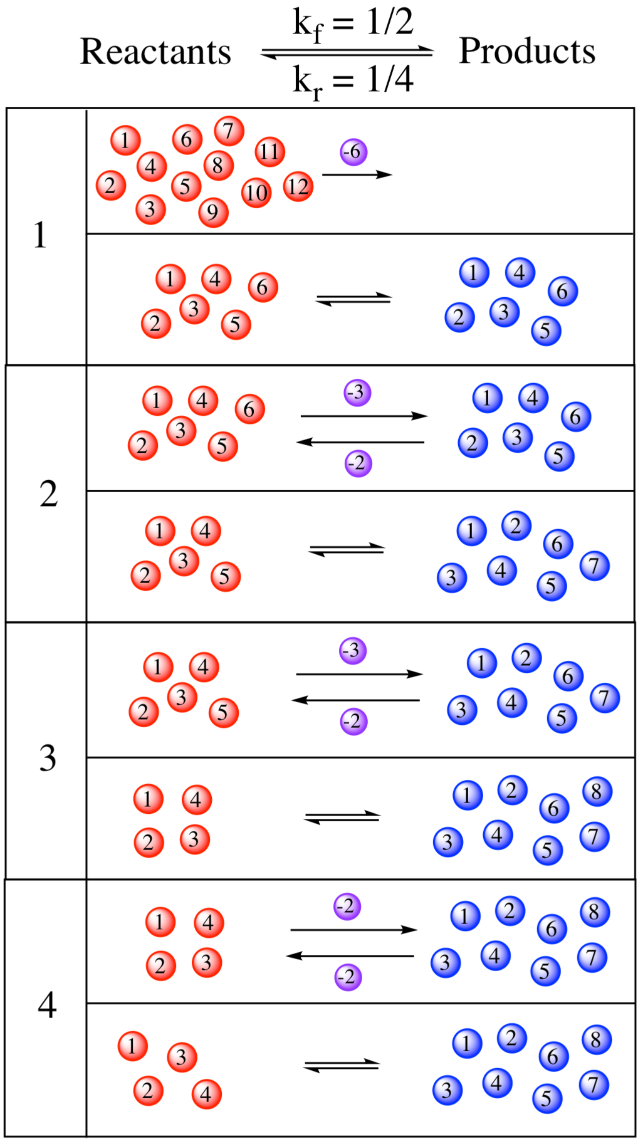
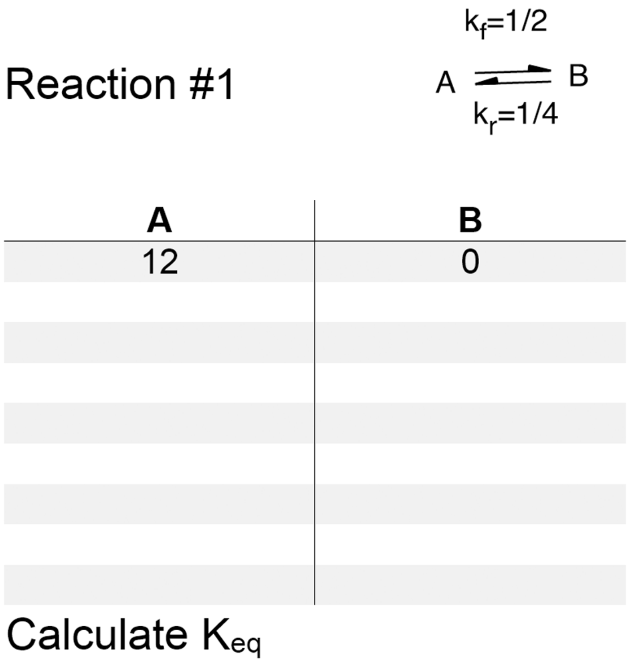


Figure 1. Illustration representing the movement of volunteer "molecules" during the demonstration.

- The instructor asks the volunteers to move again, which results in two volunteers (one-half of four from the reactant side) moving from the reactants and two volunteers (one-fourth of eight) moving from the product side as the audience records the new number of reactants (4) and products (8).
- This can be repeated as many times as needed to reinforce that the dynamic nature of equilibrium is the point where the rates of the forward and reverse reactions are now equal, *i.e.,* the same number of volunteer "molecules" are moving on both sides.



Reaction #1

$A \underset{k_r=1/4}{\overset{k_f=1/2}{\rightleftharpoons}} B$

A	B
12	0

Calculate K_{eq}

Figure 2. Sample in-class worksheet for students to track movement of molecules.

The aim is to have students link the theoretical idea of equilibrium to the concrete action of multiplying the rate constant times the concentration to determine the rate, or the number of students moving from reactants to products or vice versa. A list of questions and discussion points to probe students' understanding is given in the *Instructor Preparation* section below. All the students are then asked to calculate the equilibrium constant (K_{eq}) for the reaction by dividing the number of product molecules by the number of reactant molecules *i.e.,* using *Eq. 2*. We have included an instructor script (Supporting File S1) to assist with running the activity.

Part II: Small Groups Discussion

Next, the activity is repeated with students solving for equilibrium using the same forward and reverse rate constant, but with the twelve molecules starting as products. Students are divided into small groups, and each group is given a set of twelve candies or buttons to serve as molecules to move back and forth in the reaction. An in-class worksheet (Supporting File S2) is provided to track the movement of those items. After completion of the second equilibrium reaction, students are asked to calculate K_{eq} again, and discover that they have the same value whether or not the molecules start out as reactants or products. Two more experiments can be carried out by swapping the forward and reverse rate constants and starting with all the molecules either in the reactants or products side. Finally, students can be given the open question of how to determine K_{eq} from the rate constants data. In our experience, students quickly link K_{eq} to dividing the forward rate constant by the reverse rate constant, *i.e.,* by utilizing *Eq. 3*.

It would be helpful for instructors to point out that equilibrium is achieved when the rate of the forward reaction = the rate of the reverse reaction, but that the forward (k_f) and reverse (k_r) rate constants may be different. Using the iterations of rate constants suggested in the activity can assist with making this distinction. In order for students to visualize different reaction scenarios, instructors may also provide various rate constant values for the forward and backward reaction. For example, providing an example of a very large k_f with a very small k_r will be interesting for students to see how the reaction progresses.

Furthermore, the implications of the values of rate constants k_f and k_r should be made explicitly clear. When using the values of k_f and k_r being 1/2 and 1/4 respectively, this suggests that the reaction being modeled is product-favored. This observation is of great value to students considering that they often misconceive equilibrium as being a mixture of 50:50 reactants and products, therefore, making these inferences from their suggested rate constants is important.

Instructor Preparation

Practicing with teaching assistants or other students before running this demonstration is highly recommended as directing volunteers can be time consuming during the first 'reaction'. A designated area for reactants and products to stand is also advised. A teaching or learning assistant being present in the student groups aids in prompting discussion on how many volunteers should move before the instructor says 'react'. Volunteers should not move until instructed to do so, as oftentimes volunteers from the products side will move before the reactant side has a chance to move, which throws off the demonstration. The instructor or teaching assistant should model how to complete the first demonstration and keep up with how many volunteers are on the reactant and product sides. In addition, the questions below can assist instructors in leading the discussion about dynamic equilibrium during the activity:

- Describe how we calculate the rate for the reaction.
- Are the rate constants for the forward and reverse reactions changing? Why or why not?
- How can the concentrations of reactants and products be different, but equilibrium is reached?
- What is equal at equilibrium?
- What are the two ways by which we calculated equilibrium constant?

In our implementation of this activity, we did not have issues soliciting volunteers and found that students were enthusiastic to participate in the activity. Volunteer recruitment is an important aspect and instructors should emphasize the "fun" element of this activity while soliciting volunteers. If volunteers are hesitant, you may consider using a random selection method like drawing names or using a numbered system.

This activity was performed in a large lecture hall with stadium seating; therefore, it was easy for all students to view and track the movement of volunteers. Volunteers can also be tracked by raising their hands to indicate movement, or by holding colored paper provided by the instructor. For larger classes or limited space, an electronic simulation such as PhET (30) can be considered to model chemical reactions and equilibrium. However, strategies involving physical activity offer a unique advantage of engaging students kinesthetically through movement (31).

TEACHING DISCUSSION

During the first experiment, students observed that once equilibrium is reached, volunteers are moving back and forth, but no change in the number of molecules in products or reactants is occurring. This prompts a productive dialogue about the dynamic nature of equilibrium and illustrates why the common student misconception that the reaction halts when it attains equilibrium is incorrect. Students are asked to reflect of what quantities are equal in equilibrium; this can be used to direct the instructor to point out how the concentration for both reactants and products is different, the rate constants are different, yet the rate constant times the concentration (number of molecules in activity) is what is equal (*Eq. 1*). This is a great way to elucidate the connections between rate constants and the equilibrium constant (*Eq. 3*). After all the above equilibrium reactions are completed, the instructor begins a discussion of relating the numerical values of the rate constants to that of the equilibrium constants, *i.e.,* by dividing the forward rate constant (1/2) by the reverse rate constant (1/4). With little help, students are able to use *Eq. 3* to link the two concepts on their own due to the visual aspect of the demonstration. We have highlighted the connection between the two concepts in our Primary Image.

We administered a post-activity to students to gather information regarding what aspects of the activity worked well, and what could be improved (Table 2). Overall, student feedback was positive, and the majority of students agreed that the topic made the concept of equilibrium easier to understand. Student comments (Table 3) stated that the increased size of the "molecules," the hands-on application, and the tangible nature of the activity through explicitly showing the movement of molecules enriched their understanding of the topic. Students also mentioned that working in small groups, as well as being able to go through the movement of molecules step-by-step boosted their conceptual learning. Regarding aspects of the activity that can be improved, students noted that the process is disorganized and time-consuming in the beginning due to the recruitment of volunteers and formation of groups. To address this confusion, we have provided tips under the *Instructor Preparation* section.

We also administered short pre-activity and post-activity multiple-choice quizzes (Supporting File S3). to determine the impact of this activity on achieving the targeted student learning objectives. Students completed the pre-activity quiz in class immediately before 'Part 1' of the activity (volunteer demonstration), and the post-activity quiz was done by students immediately after 'Part 2' of the activity (small groups discussion). It is important to note that students were introduced to the concept of chemical equilibrium in the previous lecture. Analysis of student responses to the quizzes showed an overall increase in the number of correct responses in the post-activity quiz when compared to those of the pre-activity quiz (Figure 3). The gains observed for Q1 and Q2 indicated that the activity aided in illustrating the dynamic nature of chemical equilibrium and clarifying the important features of equilibrium reactions.

This activity works best in introductory approaches to chemical equilibrium. Towards the end of the lecture or in the next lectures, we recommend that instructors explicitly discuss a time-step to help students see that depending on the starting "concentrations," they may reach equilibrium more quickly or more slowly. Instructors should also point out the limitations of this activity when compared to a chemical reaction occurring in real time. Some points to note are: (i) In this activity, the reactants and products are spatially separated—which matches a written chemical equation—but in many chemical reactions

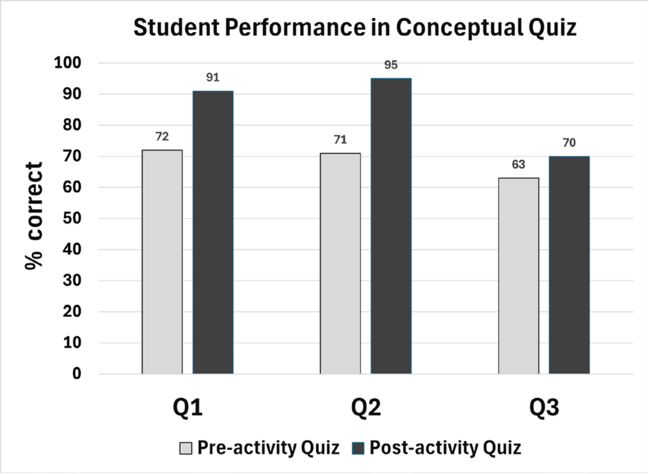


Figure 3. Student performance in the pre- and post-activity quizzes (*N* = 144).

this sort of spatial separation does not occur. (ii) There is a sense of agency and planning in this activity, but in a chemical system such "reactions" come from random collisions. Since this activity connects the topics of chemical equilibrium with chemical kinetics, it is beneficial for instructors to point out its simplification with respect to collision theory.

To better facilitate connections between the core concept of chemical equilibrium and its application in the life sciences, this topic can be followed by (i) discussing how enzyme concentration or temperature changes can influence the equilibrium point in an enzyme-mediated reaction, thus impacting physiological processes, (ii) explaining the concept of Le Chatelier's principle, which governs how a system responds to stress, and how it relates to maintaining equilibrium in biological systems, and (iii) exploring the role of equilibrium in blood pH regulation through the carbonic acid-bicarbonate buffer system for cellular function.

Conclusions

This classroom activity provides a kinesthetic and interactive route for students to acquire a perspective on the concept of dynamic chemical equilibrium. The activity was implemented in a large classroom, but it can be easily adopted in small class sizes as well. Student feedback was positive, with a majority of students confirming the effectiveness of the activity. Evaluation of pre- and post-activity quizzes indicated that the students showed gains in certain aspects of chemical equilibrium after participating in the activity. This activity has the potential to aid in imparting content-specific knowledge, and in addressing common misconceptions about chemical equilibrium. Additionally, it can also serve as a useful tool to create connections between chemical equilibrium and reaction kinetics.

This study was declared exempt by UCLA's Institutional Review Board (IRB#17-001599).

SUPPORTING MATERIALS

- S1. Dynamic Equilibrium – Instructor Script
- S2. Dynamic Equilibrium – In-Class Worksheet
- S3. Dynamic Equilibrium – Conceptual Quiz

ACKNOWLEDGMENTS

We are grateful to the Center for Education Innovation and Learning in the Sciences (CEILS) at UCLA for facilitating this activity, and the CEILS Summer Institute participants for their feedback. We thank our learning assistants and students for their enthusiastic participation.

Table 1. Teaching timeline.

Activity	Description	Estimated Time	Notes
Preparation for Class			
Printing handouts	Make 3–4 copies of the in-class worksheets for each group of 3–4 students	5 minutes	Worksheet is provided in Supporting File S2
Organizing activity objects	Instructor divides all the objects into packets of 12 objects each	10 minutes	Doing this step in advance saves in-class time
Class Session (1-Hour Class Period)			
Lesson introduction	Instructor reviews chemical equilibrium	5 minutes	Suggested open-source resource: OpenStax Chemistry 2e, Chapter 13
Distribution of worksheets	Instructor distributes copies of the worksheets to the class	3–4 minutes	This time can be cut down if students are provided the handouts as they are entering the lecture hall or if handouts have been pre-distributed in each seat
Part I: Volunteer Demonstration			
Volunteer demonstration	Instructor solicits volunteers and proceeds to perform Part I of the activity	20 minutes	Step-by-step guidelines are provided in the article and in Supporting File S1
Questions by instructor	Instructor poses questions to the students, asking them what is happening in the chemical reaction	5 minutes	Recommended questions are provided under the Instructor Preparation section
Small groups formation	Students form groups of 3–4 members	2–3 minutes	These two steps can be done simultaneously to save time
Handing out objects to groups	Instructor passes out objects to groups	2–3 minutes	
Part II: Small Groups Discussion			
Small groups discussion	Student groups proceed to perform Part II of the activity	15 minutes	Step-by-step guidelines are provided in the article
Reflection and feedback	Instructor poses questions to the class and gauges their feedback about the activity	5 minutes	If required, conceptual quiz is provided in Supporting File S3

Table 2. Student feedback data. The number of student responses and the percentage of respondents are displayed for Trial 1 (*n* = 136) and Trial 2 (*n* = 142).

Survey Question	**Number of Student Responses**	
Q1: Did the activity make the concept of equilibrium easier to understand?	**Trial 1**	**Trial 2**
Yes	121 (89%)	140 (99%)
No	15 (11%)	2 (1%)
Q2: The activity had the following features:	**Trial 1**	**Trial 2**
Interactive/student-centered	118 (87%)	135 (95%)
Made abstract concepts tangible	94 (69%)	129 (91%)
Catered to my learning style	63 (46%)	95 (67%)
Encouraged group problem solving	83 (70%)	105 (74%)
Gave adequate time for critical analysis	61 (45%)	90 (63%)

Table 3. Qualitative student comments.

What aspects of the activity did you like (made learning easier)?			What aspects of the activity did you dislike (made learning more difficult)?		
Visualization	**Tangible**	**Engagement**	**Time**	**Organization**	**Management**
• The visual representation • Increased size of atoms • Explicitly showed movement • Guided first part • Volunteers moving	• Working with objects • Physically moving candy • Tangible items • Hands on learning • Moving around the buttons	• Taking notes as we did action • Collaboration • Breaking it down in steps • Interactive and engaging • Group problem solving	• Set up took a lot of time • Went a bit fast • Getting in groups • Wish we had more time • Quiz seemed unnecessary and took time	• A little disorganized • Initially working with objects • Initial confusion • It was a little chaotic • Forming a group	• Everyone talking at once • Class chatter • Need roles in groups • Some people were loud • A little childish

REFERENCES

1. Bradbury NA. 2016. Attention span during lectures: 8 seconds, 10 minutes, or more? Adv Physiol Educ 40:509–513 doi:10.1152/advan.00109.2016.
2. Ambrose SA, Bridges MW, DiPietro M, Lovett MC, Norman MK. 2010. How learning works: Seven research-based principles for smart teaching. John Wiley & Sons, San Francisco, CA.
3. Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, Wenderoth MP. 2014. Active learning increases student performance in science, engineering, and mathematics. Proc Natl Acad Sci 111:8410–8415. doi:10.1073/pnas.1319030111.
4. Pelletreau KN, Andrews T, Armstrong N, Bedell MA, Dastoor F, Dean N, Erster S, Fata-Hartly C, Guild N, Greig H, Hall D, Knight JK, Koslowsky D, Lemons PP, Martin J, McCourt J, Merrill J, Moscarella R, Nehm R, Northington R, Olsen B, Prevost L, Stoltzfus J, Urban-Lurain M, Smith MK. 2016. A clicker-based case study that untangles student thinking about the processes in the central dogma. CourseSource 3. doi:10.24918/cs.2016.15.
5. Ramachandran R. 2019. Teaching the biological relevance of chemical kinetics using cold-blooded animal biology. CourseSource 6. doi:10.24918/cs.2019.24.
6. Wright R. 2014. Why meiosis matters: The case of the fatherless snake. CourseSource 1. doi:10.24918/cs.2014.1.
7. Walker JD, Cotner SH, Baepler PM, Decker MD. 2008. A delicate balance: Integrating active learning into a large lecture course. CBE Life Sci Educ 7:361–367. doi:10.1187/cbe.08-02-0004.
8. Armstrong N, Chang SM, Brickman M. 2007. Cooperative learning in industrial-sized biology classes. CBE Life Sci Educ 6:163–171. doi:10.1187/cbe.06-11-0200.
9. Daniel KL. 2016. Impacts of active learning on student outcomes in large-lecture biology courses. Am Biol Teach 78:651–655. doi:10.1525/abt.2016.78.8.651.
10. Raviolo A, Garritz A. 2009. Analogies in the teaching of chemical equilibrium: A synthesis/analysis of the literature. Chem Educ Res Pract 10:5–13. doi:10.1039/B901455C.
11. Nakhleh MB. 1992. Why some students don't learn chemistry: Chemical misconceptions. J Chem Educ 69:191–196. doi:101021/ed069p191.
12. BouJaoude S. 1993. Students' systematic errors when solving kinetic and chemical equilibrium problems, p 1–25. Presented at the Annual Meeting of the National Association for Research in Science Teaching (NARST). NARST, Atlanta, GA.
13. Tansey JT, Baird Jr T, Cox MM, Fox KM, Knight J, Sears D, Bell E. 2013. Foundational concepts and underlying theories for majors in "biochemistry and molecular biology." Biochem Mol Biol Educ 41:289–296. doi:10.1002/bmb.20727.
14. Wright A, Provost J, Roecklein- Canfield JA, Bell E. 2013. Essential concepts and underlying theories from physics, chemistry, and mathematics for "biochemistry and molecular biology" majors. Biochem Mol Biol Educ 41:302–308. doi:10.1002/bmb.20728.
15. Rakestraw NW. 1926. Demonstrating chemical equilibrium. J Chem Educ 3:450. doi:10.1021/ed003p450.
16. Sorum CH. 1948. Lecture demonstrations for general chemistry. J Chem Educ 25:489. doi:10.1021/ed025p489.
17. Burke BA. 1977. Chemical equilibrium. J Chem Educ 54:29. doi:10.1021/ed054p29.3.
18. Smoot F, Ragan S, Burkett AR. 1978. A demonstration of the relationship between rate constants and equilibrium constants. J Chem Educ 55:790. doi:10.1021/ed055p790.2.
19. Eilks I, Gulacar O. 2016. A colorful demonstration to visualize and inquire into essential elements of chemical equilibrium. J Chem Educ 93:1904–1907. doi:10.1021/acs.jchemed.6b00252.
20. Anderson M, Buckley A. 1996. Equilibrium constants you can smell. J Chem Educ 73:639. doi:10.1021/ed073p639.
21. Cloonan CA, Andrew JA, Nichol CA, Hutchinson JS. 2011. A simple system for observing dynamic phase equilibrium via an inquiry-based laboratory or demonstration. J Chem Educ 88:975–978. doi:10.1021/ed100846k.
22. Price DS, Brooks DW. 2012. Extensiveness and perceptions of lecture demonstrations in the high school chemistry classroom. Chem Educ Res Pract 13:420–427. doi:10.1039/c2rp20014g.
23. Ramachandran R, Sparck EM, Levis-Fitzgerald M. 2019. Investigating the effectiveness of using application-based science education videos in a general chemistry lecture course. J Chem Educ 96:479–485. doi:10.1021/acs.jchemed.8b00777.
24. Edmonson Jr LJ, Lewis DL. 1999. Equilibrium principles: A game for students. J Chem Educ 76:502. doi:10.1021/ed076p502.
25. Hanson RM. 2003. Playing-card equilibrium. J Chem Educ 80:1271–1273. doi:10.1021/ed080p1271.
26. Rogers F, Huddle PA, White MW. 2000. Simulations for teaching chemical equilibrium. J Chem Educ 77: 920–926. doi:10.1021/ed077p920.
27. Davenport JL, Leinhardt G, Greeno J, Koedinger K, Klahr D, Karabinos M, Yaron DJ. 2014. Evidence-based approaches to improving chemical equilibrium instruction. J Chem Educ 91:1517–1525. doi:10.1021/ed5002009.
28. Wilson AH. 1998. Equilibrium: A teaching/learning activity. J Chem Educ 75:1176. doi:10.1021/ed075p1176.
29. Bartholow M. 2006. Modeling dynamic equilibrium with coins. J Chem Educ 83:48A. doi:10.1021/ed083p48A.
30. Koch L, Barbera J, LeMaster, Adams W. n.d. Reversible reactions. PhET Interactive Simulations. Retrieved from https://phet.colorado.edu/en/simulations/reversible-reactions (accessed 24 June 2024).
31. Bridgeman AJ, Schmidt TW, Young NA. 2013. Using atomic orbitals and kinesthetic learning to authentically derive molecular stretching vibrations. J Chem Educ 90:889–893. doi:10.1021/ed300045q.