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RESEARCH ARTICLE

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An interactive virtual laboratory addressing student difficulty in differentiating between chemical reaction kinetics and equilibrium

Milo D. Koretsky

School of Chemical, Biological, and Environmental Engineering, Oregon State University, Corvallis, Oregon

Correspondence
Milo D. Koretsky, School of Chemical, Biological, and Environmental Engineering, 116 Johnson Hall, Oregon State University, Corvallis, OR 97331-2702.
Email: milo.koretsky@oregonstate.edu

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Abstract

The Reaction Rate vs Equilibrium Interactive Virtual Laboratory (IVL) has been developed to address a common student misconception in analyzing and designing chemical reactors—the difference between reaction kinetics and reaction equilibrium. The IVL allows students to make meaning of the difference between reaction rate and equilibrium by exploring their dependence on temperature. The design is to create a cognitive conflict between their observations of how reaction rate and equilibrium depend on temperature. In the IVL, students are guided through a set of 20 frames where they are asked to respond to questions that ask them to predict, observe, or reflect on phenomena related to the specific concept while manipulating the molecular simulations. The Reaction Rate vs Equilibrium IVL is embedded within the Concept Warehouse (available at http://cw.edudiv.org/) and the instructors can access student responses to the questions as well as an automatic grading system can be used for student assessment. In this study, the IVL was implemented in a junior-level chemical engineering thermodynamics studio class. Data sources included responses from 82 consenting students during their work with the virtual laboratory and a survey completed the day after. We examined student responses to the summative conceptual question pair near the end of the IVL to determine whether students understood the main concept. We found that 57.1% clearly understood the concept. In addition, students indicated that they found group work beneficial when using the IVLs and appreciated the visual and dynamic representation of molecular phenomena.

KEYWORDS

chemical engineering, misconception, reaction equilibrium, reaction rate, virtual laboratory

1 | INTRODUCTION

Central to the work of chemical engineers is developing strategies to improve the yield of useful chemical products with the minimum consumption of energy. Correspondingly, in most reactor design courses, students need to learn how to approach reactor design when yield is limited by equilibrium, such as for ammonia or methanol synthesis [9]. However, this learning outcome becomes problematic for those students who bring a common misconception—the inability to distinguish between chemical reaction rate (i.e., kinetics or how fast a reaction proceeds) and chemical reaction equilibrium (i.e., thermodynamics or the extent to which is ultimately reacts) [1,3]. In this article, we describe the development and implementation of an Interactive Virtual Laboratory (IVL), the Reaction Rate vs Equilibrium IVL, that uses the strategy of cognitive conflict to help students organize their understanding to distinguish between chemical reaction rate and chemical reaction equilibrium.

Three research questions are examined in this study:

(i) Do students understand the key concepts after completing the Reaction Rate vs Equilibrium IVL?
(ii) How do students perceive the Reaction Rate vs Equilibrium IVL with regard to learning gains, usability, engagement with the IVL, and the value of using the IVL?
(iii) What specific strengths, limitations, and technical problems do students identify?

2 | BACKGROUND

As technology becomes more integrated into classroom instruction, virtual laboratories are receiving attention as an alternative way to engage students and promote learning [2,8,15]. Physics educators at the University of Colorado have developed a set of virtual laboratories they call PhETs that allow students to explore representations of physics phenomena, some of which are impossible to view in a physical laboratory environment [23]. The PhET simulations are designed to allow students to construct their own understanding of physics and are useful as a part of learning activities in class [16]. PhET simulations are open ended, so learning activities need to guide, but not constrain, students using them. Research on this type of virtual laboratory has shown that it significantly improves learning [6,25].

Connected Chemistry [18] is amongst the set of virtual laboratories based on the multiagent NetLogo model. These virtual laboratories are targeted for high school chemistry students and designed to assist them with understanding chemistry phenomena by displaying visual representations of molecular kinetics. They allow students to see how macroscopic behavior arises from microscopic interactions. The Connected Chemistry simulations can be used as a visualization tool for abstract concepts, a laboratory simulator to allow students to relate laboratory and classroom knowledge, and as a feedback tool for students working on individual assignments. Students who have completed the Connected Chemistry simulations have been shown to demonstrate a better understanding of micro-level phenomena [12,13].

We have designed the IVLs to target important engineering concepts, similar to what PhETs provide for physics education and Connected Chemistry provides for chemistry education. However, unlike PhETs and Connected Chemistry, the IVLs are explicitly scaffolded. Although they do allow experimentation, they are not open-ended sandbox environments. Instead, students are guided by prompts and must answer a variety of different types of questions as they proceed. In this way, students are directed to interact with the IVLs in intentional ways as they engage with complex content to construct understanding. The approach taken in designing them was to target a specific thermodynamics concept in each IVL. Ideally, students who encounter a new concept while working with the IVLs will undergo some form of cognitive conflict.

Posner et al. [17] describe four conditions which must be fulfilled for a conceptual change to occur. There must be dissatisfaction with existing conditions, a new conception must be intelligible, a new conception must appear initially plausible, and a new concept should suggest the possibility of a fruitful resolution. Limón [14] describes the first step, the dissatisfaction, as a form of cognitive conflict, wherein learners encounter anomalous and conflicting data, forcing them to reorganize their understanding. We propose that virtual laboratories can serve as an effective medium for creating cognitive conflict that leads to improved conceptual understanding in students. The IVLs are designed to present students with guided experiences that affirm correct conceptions while creating a cognitive conflict for students whose conceptions are incorrect or underdeveloped. In this article, we illustrate this idea with one of several IVLs we have developed, the Reaction Rate vs Equilibrium IVL.

The Reaction Rate vs Equilibrium IVL, focuses on the distinction between chemical reaction rate (i.e., kinetics or how fast) and chemical reaction equilibrium (i.e., thermodynamics or the extent). Being unable to appropriately distinguish between rate and extent of chemical reaction has been troublesome for chemistry students at all levels, as reported by several chemistry researchers [1,3]. Wheeler and Kass [22] identified it as one of six misconceptions in equilibrium on their Misconception Identification Test, developed for chemistry students over 30 years ago, but confusions of rate versus equilibrium are rarely addressed by chemical engineering educators [4]. In three of the five items of the chemistry Misconception Identification Test, the majority of senior high school students chose a single attractive distractor (incorrect answer choice), and only for one question did the majority students answer correctly. In a study of Hungarian university chemistry students, researchers elaborated on the nature of this misconception. They found that one of the main sources of misunderstanding chemical reactions comes from mixing concepts of kinetics and thermodynamics. Specifically, they found that students believed that a higher equilibrium constant always denotes a greater reaction rate [21]. Similarly, a study of college-level physical chemistry students' misconceptions identified "using kinetics concepts to explain thermodynamics concepts" as a recurring theme. This theme was present in misconceptions like believing the reason temperature affects equilibrium composition is because temperature affects the rate of reaction [20]. In addition, a study collecting expert observers' selection of key student misconceptions in chemistry identified the belief that increasing temperature increases the reverse reaction rate but decreases the forward reaction rate as a common misconception [7].

We next describe the Reaction Rate vs Equilibrium IVL designed to elicit cognitive conflict in chemical engineering students who brought such confusions to their more advanced chemical engineering coursework.

3 | THE REACTION RATE VS EQUILIBRIUM INTERACTIVE VIRTUAL LABORATORY

3.1 | Overview

The Reaction Rate vs Equilibrium IVL was designed to address the common student misconception about the distinction between reaction rate (how fast a reaction occurs) and equilibrium (the distribution of species when there is no more tendency to change). The IVL allows students to make meaning of the difference between reaction rate and equilibrium by exploring their dependence on temperature. While students often predict correctly that reaction rates for a simple ideal gas reaction will become faster at higher temperatures, they also often mistakenly think that the reaction equilibrium will shift towards the products at higher temperatures as well.

In the IVL, students observe an exothermic reaction at three different temperatures, allowing them to see how temperature affects equilibrium constant and reaction rate constant. The design is to create a cognitive conflict between their observations of how reaction rate and equilibrium depend on temperature. As temperature increases, the reaction rate also increases but the equilibrium constant decreases as the reactants become more favored over the products. The design intent is for this type of cognitive conflict to help students clarify and explicitly differentiate between the reaction rate and reaction equilibrium.

3.2 | IVL design

In the IVLs, students are guided through a set of frames where they are asked to respond to questions that ask them to predict, observe, or reflect on phenomena related to the specific concept [5]. Figure 1 presents a screenshot of one of the 20 frames of the Reaction Rate vs Equilibrium IVL. The figure illustrates the three main parts of each of the 20 frames: (a) a box containing the molecular simulation that students are tasked with manipulating in certain ways—in this IVL, students enable and disable reactions; (b) a macroscopic, graphical representation of the simulated phenomena (located to the right of the molecular simulation); and (c) a box to read instructions and provide answers to questions (below the molecular simulation).

To complete the Reaction Rate vs Equilibrium IVL, students provide answers to questions in the 20 frames while manipulating the molecular simulations at three different temperatures. Students predict how the rate and equilibrium conversion change as temperature changes. For this exothermic reaction, they then observe the rate increases with temperature while the equilibrium conversion decreases. To make sense of these conflicting results, students need to identify and distinguish between concepts of rate and equilibrium and thus organize their thinking around these concepts. Such a strategy would not work with endothermic reactions since both rate and equilibrium conversion increase as temperature increases.

The 20 questions have been classified into four categories: procedural, reflection, prediction, and conceptual. Figure 2 shows screenshots of each question type (corresponding the the "question prompt" box in Figure 1). Procedural questions (five questions) require computation or graphical interpretation and the answers are typically numerical. Reflection questions (seven questions) require students to think back to previous problems and compare how the results differ due to changes. Prediction questions (two questions) require students to anticipate what will happen if they make a change to the system. Conceptual questions (six questions) require students to interpret data or information to explain complex phenomena happening in the IVL.

The Reaction Rate vs Equilibrium IVL is embedded within the Concept Warehouse [11] (available at http://cw.edudiv.org/). Figure 3 shows a screenshot of the assignment screen available to instructors. The associated database is used to store student responses to all of the questions. Through the Concept Warehouse Instructor Interface, instructors can access student responses to the questions (see Figure 4) as well as see how often students

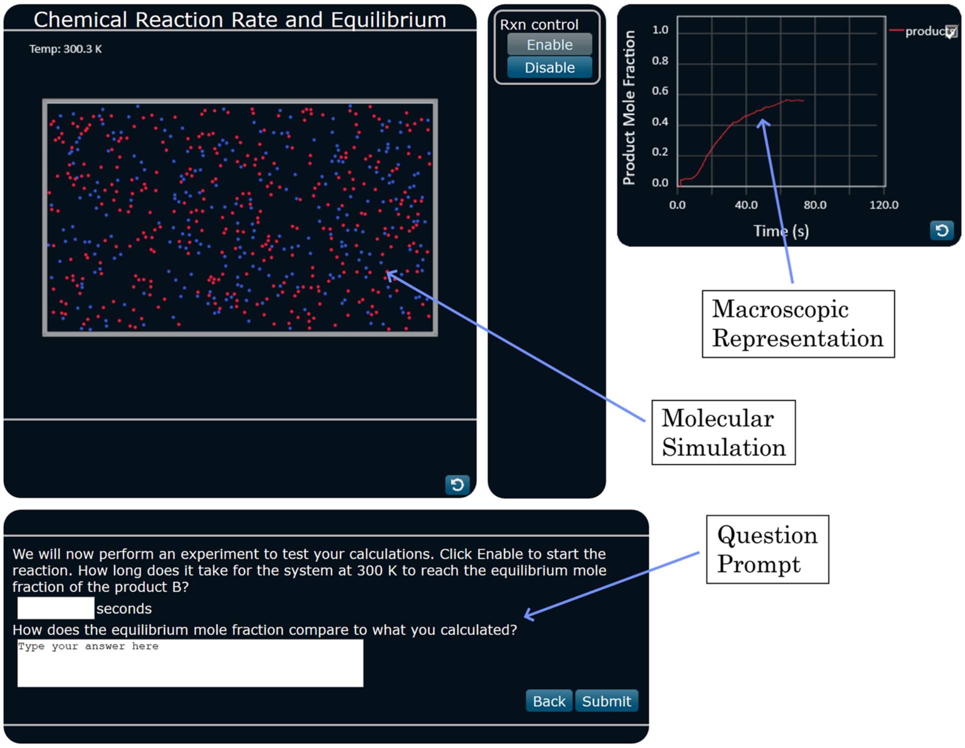

FIGURE 1 Students explore the difference between reaction rate and equilibrium by performing the same reaction at three different temperatures. The reaction is exothermic, so as temperature increases, equilibrium shifts to favor the reactants but the rate increases. This reaction takes place at 300 K. The three text boxes point to the different components of the Interactive Virtual Laboratory (IVL)

performed certain actions, such as refreshing the molecular simulation. In addition, an automatic grading system can be used for student assessment. This architecture provides a large amount of information about student thinking (e.g., approximately 2,000 responses for the 50 min implementation in this study). One of the long-term goals of the IVL project is to learn ways that instructors and education researchers can extract meaningful information from this type of data set and feed it back to improve student learning.

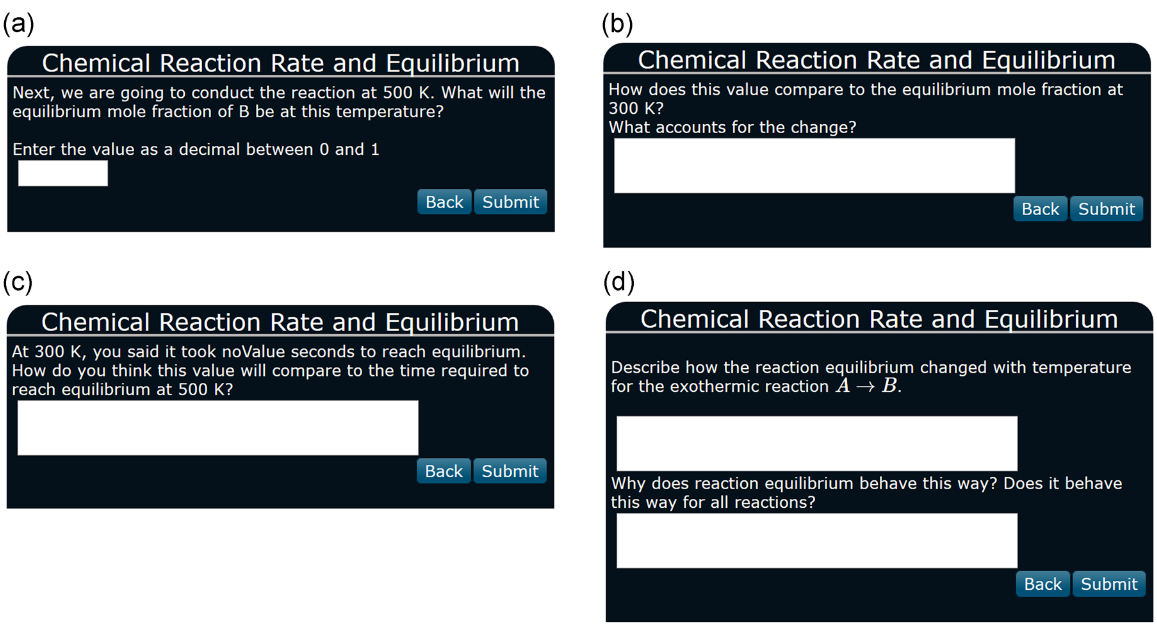

FIGURE 2 Screenshots of four different question prompts in the Rate vs Equilibrium IVL, including (a) procedural questions (five questions), (b) reflection questions (seven questions), (c) prediction questions (two questions), and (d) conceptual questions (six questions).

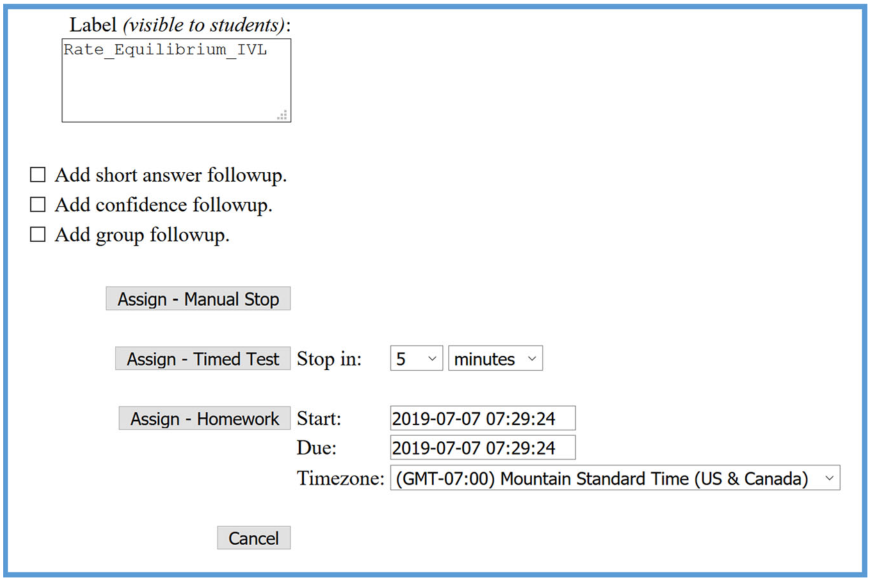

FIGURE 3 Screenshot of the Instructor Interface to assign the Rate vs Equilibrium IVL through the Concept Warehouse. IVL, Interactive Virtual Laboratory

Why is the reaction not proceeding?	Although it appears nothing is happening, there is a non-zero rate constant in the forward direction. What will be the mole fraction of B if you wait for a very long time?	Describe how the reaction equilibrium changed with temperature for the exothermic reaction ##A \rightarrow B##.	Why does reaction equilibrium behave this way? Does it behave this way for all reactions?	Describe how the reaction rate changed with temperature for the exothermic reaction ##A \rightarrow B##.	Why does the reaction rate behave this way? Does it behave this way for all reactions?	Identify and describe in 1-2 sentences the most important concepts about reaction kinetics and equilibria this interactive virtual laboratory addressed.	How do these concepts connect to what you have been learning in class?
The temperature is not high enough for the reaction to proceed. Due to a lack of energy to get the molecules to react. This can be related to reaction rate effects due to temperature.	The mole fraction of B will tend to 0.	the reaction equilibrium decreased as the temperature increased.	It behaves this way because A is more entropically favored.	equillibrium decreased when temperature increased.	A is more entropically favored	The higher the temperature, the lower the equilibrium mole fraction due to what entropy favors the most.	Entropy is tied into everything in thermo!
The reaction temperature is not high enough for the energy for the needed reaction	0.93	It increases K with lower temperature which influences the equilibrium compositions.	In a closed system equilibrium is reached and based off of K. It would not be the same for every reaction.	The reaction rate increased with temperature and so influenced the reactions time to equilibrium	As temperature is increased energy is increased thus influencing the reaction. Yes as kinetic energy increases and more reactions could be possible	How temperature can influence the rate and composition of a reaction based on concepts learned in lecture in a	Connecting to the concepts learned in lecture with reactions rates and K values but seeing it helped solidify the concept in my mind

FIGURE 4 Screen shots of part of the analytics available through the Concept Warehouse. In this case, two students' responses to the last eight questions are displayed. In the tool, the instructor has access to all student answers

4 | METHODS

4.1 | Context

The Reaction Rate vs Equilibrium IVL was implemented in a junior-level chemical engineering thermodynamics studio. Studios have been shown to be a well-received strategy in response to the effects of increased enrollment [10]. During a normal studio session, the approximately 100 students in the class are divided into sections of 25, and students complete a paper worksheet covering conceptual thermodynamics topics. Students are asked to work in groups of about three and can ask for help from a teaching assistant while completing the worksheet. On the day the IVL was implemented, students were asked to bring a laptop to class to access the Reaction Rate vs Equilibrium IVL and directed to work through the entire IVL individually in the 50 min allotted for class. However, they were also encouraged to discuss the IVL with their group at any time they were confused or stumped on how to answer. Students answered all discussion questions directly through the IVL prompt, but were also given a worksheet to work through the prompts that required calculations. A teaching assistant was available for any students who had difficulty accessing the IVL or questions relating to the IVL topics.

4.2 | Data sources

Two data source were used in this study. First, student responses were collected through the database of the Concept Warehouse as they completed the IVL. Second, the day after the IVL activity, students were asked to score a series of 12 statements on a Likert scale ranging between 1 (complete disagreement) and 5 (complete agreement). Each statement was designed for students to assess one of four aspects of the IVL: student engagement with the IVL, learning gains from IVL use, the usability of the IVL, and the value of using the IVL. Students were also asked two free response questions (a) to describe any technical difficulties they experienced and (b) indicate strengths or limitations of the IVL.

While data were collected from all students, only data from students who agreed to participate in the study and signed an IRB informed consent form are used in this study ($n = 82$).

4.3 | Data analysis

To answer the first research question, we analyzed student responses to several procedural questions. We examined three similar questions asking students to calculate equilibrium product mole fraction at 300, 500, and 100 K, in that order. Students were given the enthalpy and entropy of reaction, but were not given access to a molecular representation. We checked to see how many of the students correctly calculated the equilibrium product mole fraction for each of the three questions to see if there was a tendency for students to improve over time. The IVLs allow students to go back and change previous answers. In the case of multiple responses, only the first response from the student was scored. In this way, we can be certain that students did not get the answer from the graphs on the following frame. We also examined the question shown in Figure 1 and its corresponding question at 500 K. In these questions, students were asked to enable a reaction, and then observe the reaction until it reached equilibrium. Students were provided with a graph showing product mole fraction as a function of time. The time axis begins recording data as soon as students enter the page, not when they enable the reaction. By looking at this response, we wished to find whether students were able to interpret the graphs correctly.

In addition, we examined two summative conceptual questions at the end of the Reaction Rate vs Equilibrium IVL, shown below. Each question was formatted in a similar way and was designed to assess if students were able to understand the main concept being addressed by the IVL. Unlike for the procedural questions, only the last response was scored in the case of multiple answer submissions.

> *Questions 1: "Describe how the reaction* ***equilibrium*** *changed with temperature for the exothermic reaction A→B. Why does reaction equilibrium behave this way? Does it behave this way for all reactions?"*

> *Questions 2: "Describe how the reaction* ***rate*** *changed with temperature for the exothermic reaction A→B. Why does reaction rate behave this way? Does it behave this way for all reactions?"*

We chose this set of two questions to analyze because they prompt students to examine the differences between reaction rate and equilibrium to answer the questions. When examining the IVL responses, we looked for clear indications that the students could distinguish between effects of temperature on reaction rate and equilibrium. We did not look for an explicit comparative statement because the two questions were asked separately. Instead, we looked at how the students answered the two questions to see if they described the two effects differently. Any student who could clearly distinguish between effects of temperature on reaction rate and equilibrium was given a score of "correct." Below is an example of a student who received a score of "correct" based on the two responses.

> "Correct" Response to Question 1: *"This processes behaves this way because it is an exothermic reaction and follows Le Chatelier's Principle. Not all reactions behave this way, although they do follow Le Chatelier's Principle. An endothermic reaction would behave in the opposite way."*

> "Correct" Response to Question 2: *"Reaction rate always behaves this way because a higher temperature increases the number of collisions due to an increase in kinetic energy and increases the energy of the molecules such that they can more easily overcome the activation barrier."*

In the answer to Question 1, the student indicates that not all reactions favor the reactants more when temperature increases by using the counterexample of endothermic reactions and invoking Le Chatelier's Principle. While the second answer is not entirely correct—some complex reaction rates actually *do* decrease when temperature is increased—explaining the rate effects with activation energy instead of reaction enthalpy was sufficient to show that the student was able to decouple the concepts of reaction rate and equilibrium. In contrast, the following is an example of a student who was scored as "incorrect" based on the two responses.

> *"Incorrect" Response to Question 1: "No, because we have a positive dH (exothermic reaction)."*

> *"Incorrect" Response to Question 2: "by increasing the temperature we are lowering the mole fraction of B and K is decreasing lowering the reaction rate."*

The first response does not correctly answer Question 1. The reaction is exothermic; however, the change in enthalpy is negative rather than positive. The student also says the reaction rate and equilibrium constant are both lowered with increasing temperature, which shows that the student has not been able to distinguish between the distinct concepts of reaction rate and equilibrium.

In addition to "correct" and "incorrect," a number of students were scored as "incomplete" because their responses were too fragmented to give a clear indication of their thinking. The following is an example of a student scored as "incomplete."

> *"Incomplete" Response to Question 1: "Because the system is exothermic."*

> *"Incomplete" Response to Question 2: "because it is exothermic."*

The two responses do not fully answer either of the questions. Presumably, the student means that the reaction favors the products less as temperature increases because it is exothermic. However, nowhere in the two responses does the student say anything about rate and its dependence on temperature. There is not enough information present in the responses to show whether the student did or did not understand the main concept.

Using these guidelines, two researchers independently coded each question pair as correct, incorrect, or incomplete yielding acceptable reproducibility (88% agreement; Cohen's $\kappa = 0.80$)

To answer the second research question about student perception, we examined the results of the Likert scale statements by averaging the student responses to each statement. The three items that used reverse scales were inverted to align with the other items; that is, if an item received an average of 2.0 on the reverse scale it would be reported as 4.0. To answer the third research question, we analyzed student responses to the free response questions asking for strengths and limitations and technical difficulties. We were particularly interested in recurring themes such as common technical difficulties or features frequently perceived as strengths.

5 | RESULTS

5.1 | RQ1: Do students understand the key concept after completing the Interactive Virtual Lab?

A summary of results to the procedural questions and summative conceptual question pair is shown in Table 1. The rate at 100 K was intentionally too slow for students to be able to observe so no values were submitted.

The three computational procedural questions were intended to provide students with an opportunity to calculate equilibrium product mole fractions and compare them to the result observed in the experiment in the IVL. The reaction in the IVL was exothermic, so the product mole fraction decreases as temperature increases. Students who were within 0.05 of the correct answer were marked

TABLE 1 The results from the computational procedural questions

	Question	
Temperature (K)	**Equilibrium calculation (%)**	**Time (rate) estimation**
300	85.4	47.6%
500	88.9	74.1%
100	82.7	N/A
Conceptual	57.1% correct; 18.2% incorrect; 24.7% incomplete	

Note: Percentages reported are for those students who calculated a value correctly or received a score of "correct" on the discussion questions

as correct within one significant figure. Eighty two students provided an answer for the calculation at 300 K, while 81 provided an answer for the calculations at 500 and 100 K. Of the students who responded, 70 (85.4%) answered correctly for 300 K, 72 (88.9%) answered correctly at 500 K, and 67 (82.7%) answered correctly at 100 K. These results indicate that a similar number of students initially answered the problem correctly when answering the three questions. The three calculations were very similar. In fact, the second and third calculation could be solved by changing only a single number from the first. It is possible that students who used the wrong method of calculating the first answer continued to use an incorrect method on the second and third question even though the answer did not agree with the simulated experiment.

The other procedural questions asked students to interpret graphs from the experiment (see Figure 1) and determine the time it takes for equilibrium to be established. Any student who was within 15 s of the correct answer was marked as correct. Of the 82 students who responded to the question at 300 K, only 39 (47.6%) answered correctly, while eight (9.76%) gave a value at least 15 s below and 35 (42.7%) gave a value at least 15 s above. Of the 81 students who responded at 500 K, 60 (74.1%) answered correctly while 21 (25.9%) answered at least 15 s above the correct answer. While the low values likely indicate that the student was unable to properly read the axes of the graph, the high values may be explained differently. As mentioned earlier, the graph of product mole fraction as a function of time starts tracking data as soon as the student enters the page. The graph is flat until the student enables the reaction, at which point it approaches the equilibrium value. We intended for students to take the time interval between when they enabled the reaction and when it reached equilibrium. Students who gave values that were too high may have taken the entire time interval before the reaction reached equilibrium, including the time before they enabled the reaction. This result indicates an unexpected difficulty. In future versions of the Reaction Rate vs Equilibrium IVL, we will include an additional discussion question asking students to explain how they determined the amount of time it took to reach equilibrium. This type of discussion question would require students to examine their thinking and hopefully create a form of cognitive conflict, reducing the number of students who give an incorrect response.

In total, 77 students answered both summative conceptual questions. For the question pair, 44 students (57.1%) obtained a score of "correct," 14 (18.2%) a score of "incorrect," and 19 (24.7%) a score of "incomplete." Most students were able to explain the main concept of the IVL. Unfortunately, a sizeable portion of students were unclear in whether they understood the concept or not. Students were not graded based on correct answers. Their grade on the assignment was based on completing all the questions. It is possible that many students did not answer the questions fully because there was no grade pressure. At this point, we cannot determine if the students who did not answer correctly did so because they did not understand the concept or because they lacked motivation.

5.2 | RQ2: How do students perceive the Interactive Virtual Lab with regard to learning gains, usability, engagement with the IVL, and the value of using the IVL?

Student responses to the Likert scale statements were examined to find student perceptions. The responses for each of the 12 statements were averaged and are presented in Table 2. Each statement was created with the intent to assess a particular aspect of IVL use. Two statements assessed how engaged students were while using the IVL, four assessed how well students thought the IVL helped them to learn, three assessed the usability of the IVL, and three assessed the value of using the IVL in class. The results provide indication for how students view the IVLs, as well as show areas to improve.

Student responses to all Likert scale statements were positive. The first two statements were designed to assess student engagement with the IVLs. Average responses to both statements show that students generally believe that the IVLs are an engaging activity, in that they are fun and absorbing. The IVLs were designed specifically to be highly interactive and to be more engaging than regular paper worksheets to help motivate students to learn. In this respect, student views towards IVL engagement are encouraging.

The third, fourth, fifth, and sixth statements were all designed to assess how students perceived learning gains while using the IVL. Of particular interest is the first of these

TABLE 2 Post-IVL perception questions

Statement	Average	St Dev	5	4	3	2	1	Construct
1. Time passed quickly during the Interactive Computer Simulation	3.69	0.93	17	37	25	8	1	Engagement
2. The Interactive Computer Simulation was a fun activity	3.61	0.77	7	47	25	8	0	Engagement
3. It was useful to discuss aspects of the Interactive Computer Simulation with students in my group	4.11	0.72	25	50	9	3	0	Learning
4. The Interactive Computer Simulation helped me understand the principle(s) that the instructor wanted me to learn	3.91	0.56	9	63	15	1	0	Learning
5. Observing the molecules' behavior helped me learn	3.69	0.86	9	53	13	10	1	Learning
6. I could successfully complete the activity without really understanding the material (reverse)	3.57	0.89	2	7	27	40	10	Learning
7. The Interactive Computer Simulation was easy to use	4.04	0.79	23	47	10	5	0	Usability
8. I understood the questions that I was asked to answer during the activity	3.98	0.63	15	55	15	1	0	Usability
9. I had technical difficulties with the Interactive Computer simulation (reverse)	3.75	1.21	6	11	8	36	26	Usability
10. The Interactive Computer Simulation was worth doing	3.84	0.70	10	58	14	5	0	Value
11. I would like to see Interactive Computer Simulations for other topics in the curriculum	3.82	0.77	14	48	20	5	0	Value
12. I would have preferred a regular studio activity instead of the Interactive Computer Simulation (reverse)	3.28	0.91	4	12	30	38	3	Value

Note: A score of 5 represents complete agreement with the statement, while a score of 1 represents complete disagreement. The average score for each statement is presented along with which construct the statement was designed to assess. Statements which were negative towards the IVLs have average scores reversed for convenience
Abbreviation: IVL, Interactive Virtual Laboratory

statements, which declares that working in groups is useful for completing the IVL. This statement achieved the highest agreement out of all the statements. The IVLs were designed with group discussion in mind. The response to this statement possibly indicates that they help students learn best when they are able to work in groups rather than individually. Another highly rated statement in this category assessed whether the IVL helped students learn the main principle. The high rating for this statement contrasts with the relatively low number of students who scored correct for the main conceptual question, possibly indicating an over-confident bias on the part of the students.

All three statements assessing student perception of IVL usability were scored highly by students. IVL ease of use and question quality were scored particularly highly. This result is encouraging because it shows that the transition into using IVLs is relatively easy for students. Another statement assessing student technical difficulties received a slightly lower score. Specific technical difficulties that students encountered are explored further in the discussion of the third research question.

The final three statements assessed how students perceived the value of using the IVLs in the classroom. The first two were used to determine whether students found the IVL and future IVLs worth doing. Both were rated fairly highly. However, the final statement received the lowest score out of all 12 statements. It assessed if students would have preferred to do a regular paper worksheet rather than the IVLs. Students may possibly see the IVLs as interchangeable with regular worksheets in class.

5.3 | RQ3: What specific strengths and limitations did students find with the IVL, and did students have any technical problems?

We looked specifically for recurring responses while analyzing the two follow-up questions. A recurring strength that students noted about the IVL was its capacity to facilitate visual learners through the display of dynamic molecular behavior. One student said, "… it guides students better than a normal worksheet would. Because we can see the molecular interactions, it helps us see what the answer could be rather than making us guess or ask the TA for help." The student indicates that by providing a dynamic visualization of molecular kinetics and equilibrium, the IVLs provide students with an intuitive sense of what is occurring, something not present in normal worksheets. Another student added, "A strength is actually seeing how the molecules interact with each other which is missed in live experiments." A second strength that students noted was its value for teamwork, reinforcing its high rating on the Likert scale questions. For example, one student said, "It really get you involved with your group and think as a team." The

IVLs were not designed to be specifically completed as a team. However, it may be beneficial to add team discussion sections in some of the IVLs to better facilitate group interaction.

A common limitation students noted was that the IVLs do not immediately tell students whether their answers are right or wrong. One student said, “The limitation that I see is that no one can tell me whether I answered those questions correct or not.” Another student said, “It would be nice to see the answers after you submitted your answer, to know if you were on the right track or not, it’s hard to know if you understand the concept fully when you don’t know what the correct answer really is.” Immediate answer feedback was intentionally avoided during the development of the IVLs. Our concern was that if students were presented with the correct answer, they would no longer try to develop their own understanding of the concept, but rather replace any old answers with the correct response. However, students do have ways to check their numerical answers with the IVL. For example, the systems show the product mole fraction when the reaction reaches equilibrium, allowing students to check if their previous calculations were correct. The IVLs do not provide checks for the discussion questions. Our goal was for students to piece together the main conceptual idea by doing repeated experiments in the IVL, which at least 57% of students were able to do.

Most students who reported technical difficulties were related to the IVL resetting. For example, if a student lost connection with the Concept Warehouse due to computer or internet connection failure, they were forced to start over from the beginning. One student said, “when I reached the middle of the simulation and had to do the rest of it after class, I closed my laptop and when I was back home and open the laptop again and log in, all the data I submit was gone and I had to do it again.” The IVLs currently rely on student web browsers to keep track of and retain information, including student responses. The IVL data are lost when a student refreshes the web page. One student also noted that a complete reset puts pressure on students to complete the IVL quickly: “My main complaint was that I had to rush to finish it when time was up, because I knew it would otherwise completely reset.” We acknowledge that it is inconvenient for students to restart the IVL from the beginning when the page is refreshed and have recently improved the IVLs to make them open up to the page of the last response submitted to the AIChE Concept Warehouse. Other students also said they would like the reactions in the IVL to proceed more rapidly. The Reaction Rate vs Equilibrium IVL has two reactions that require waiting, and the longest reaction takes 2 min. While we take the students’ recommendations into account, we intentionally designed this reaction to take 2 min to contrast with the second, shorter reaction that takes less than 20 s to provide an embodied sense of rate.

6 | DISCUSSION

This study examined the implementation of an IVL in a 3rd-year undergraduate chemical engineering thermodynamics course. The IVL was constructed to help students better understand differences between chemical reaction rate and chemical reaction equilibrium. During IVL activity, they completed 20 frames built around molecular and macroscopic representations of an exothermic reaction as a database collected their responses. We investigated 82 students’ responses as they completed the activity as well as their perceptions of it through a survey instrument. As they worked through the IVL, they needed to reconcile opposite trends to changing temperature—where rate increases with increasing temperature, but equilibrium conversion decreases with increasing temperature.

Our study has several limitations. We examined only one cohort of students and the study was conducted in the academic unit where the technology was developed. While the development team contained members with both content expertise and experience in creating educational technology, we did not conduct a formal evaluation and validation process other than the use of this IVL as a beta test to 225 students at two institutions outside of where it was created followed by instructor interviews. Despite these limitations, we gained knowledge about how technology can be used in collaborative environments to support conceptual understanding.

We observed a high percentage of correct responses (82.7–88.9%) to the procedural questions that asked straightforward calculations of equilibrium conversion. After each calculation, students could observe the resulting conversion through experimentation in the next frame and students whose calculations were not correct would note a discrepancy between observed and predicted values. However, in most cases, this discrepancy did not lead to procedural changes in the later frames (at different temperatures) that led them to calculate the correct answer. In addition, students expressed desire to have the correct answer of such quantitative problems immediately displayed upon answer submission. One plausible explanation is that in this type of technology-based learning environment, students expect explicit and immediate feedback of correctness. By contrast, in engineering practice it is important to develop skills to judge correctness and modify approaches if needed.

Research is needed on the alignment between student expectations of feedback in technology-based environments relative to the skills and habits of mind we seek in professional formation.

The second procedural question asked students to interpret a graphical representation to determine a reaction time. In one case, less than half the students (47.6%) were able to interpret the representation correctly, apparently erroneously including the time before they enabled the reaction as part of their estimate. It appears many students were unable to connect how the graph was representing the experiment they conducted to what the question was asking. At the same time, their self-analysis of their engagement (Table 2, Items 1, 2) and learning (Table 2, Items 3–6) were positive. More work is needed on understanding and developing students' representational fluency in these environments.

We examined student responses to the summative conceptual question pair near the end of the IVL to determine whether students understood the main concept. We found that 57.1% of responses indicated the students clearly understood the concept, 18.2% indicated they clearly did not, and 24.7% were too incomplete for us to infer understanding. While around 85% of students could answer the straightforward procedural question (as discussed above), only 57.1% of students clearly articulated the main differences between reaction rate and equilibrium in the summative question pair. However, many researchers have reported student difficulty in distinguishing rate and equilibrium. The percentage correct in this study compares favorably to those reported in the literature, where commonly only about 30% of students are able to distinguish the difference between rate and equilibrium [19,24]. In one case, less than 5% of students were able to distinguish the difference [21]. In addition, 24.7% of the responses in the IVL were coded as incomplete and some of those students may have productive conceptions that they did not adequately express. While there is opportunity for future develop this tool so that even more students can clearly articulate these differences, these results suggest that in this case the IVL was a relatively productive tool in helping students address the reaction rate versus equilibrium misconception.

In addition, students were asked to rate a set of 12 statements regarding the IVL on a Likert scale. Responses to all statements were positive towards the IVL. In particular, students indicated that they found group work beneficial when using the IVLs, something which will be considered in further development. Students were also asked for feedback regarding strengths and limitations of the IVL and any technical difficulties. The main strength that students noted was that the IVL provided a visual and dynamic representation of molecular phenomena, something not seen in books. Almost all technical difficulties students encountered were related to the loss of data upon refreshing the web page while using the IVL. Based on this study, we have implemented a way to start students at the last answered question upon re-entering the IVL so they do not lose data.

In total, 82 students participated in this study, submitting 2,103 responses. The IVLs and Concept Warehouse provide a way to gather large amounts of data. There are many opportunities to learn information on how students learn, engage, and construct knowledge but we still need to determine the ways to best interpret the data. Particularly, we require feedback from institutions to help improve both the IVLs and our data collection methods. The IVLs are available for instructors to use through the Concept Warehouse website (http://cw.edudiv.org/).

7 | CONCLUSIONS

This study provides insight in the ways virtual laboratories can provide engineering students interactive experiences to develop understanding of challenging concepts. While most students were able to complete straightforward procedural calculations, fewer were able to interpret of graphical representations or articulate the key concepts addressed in the IVL. However, the fraction of students demonstrating normative conceptual understanding of reaction rate versus equilibrium was about twice that reported elsewhere in the literature. Most students who did not get the straightforward calculation correct initially where unlikely to use information available in the IVL to adequately modify their approaches. Moreover, survey comments indicated they did not connect the information from the experiment to the value they calculated. Developers and users of technology need to identify places where students form "technology habits of mind" that go counter to "engineering habits of mind" such as wanting immediate answers rather than making meaning of the information they do have available. Finally, students viewed the opportunity to work collaboratively in this environment as useful to making progress. Developers and instructors should consider expanding their notions of distributed thinking with technology from individual and machine to also include interaction with peers.

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ORCID

Milo D. Koretsky http://orcid.org/0000-0002-6887-4527

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AUTHOR BIOGRAPHY

Milo Koretsky is a Professor of Chemical Engineering at Oregon State University. He received his B.S. and M.S. degrees from UC San Diego and his Ph.D. from UC Berkeley, all in Chemical Engineering. His research group works on integrating technology into effective educational practices that promote the use of higher-level cognitive and social skills in engineering problem solving and in promoting change towards motivating faculty to use evidence-based instructional practices.

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