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Activity

Impact of Ocean Acidification on Shelled Organisms: Supporting Integration of Chemistry and Biology Knowledge through Multidisciplinary Activities

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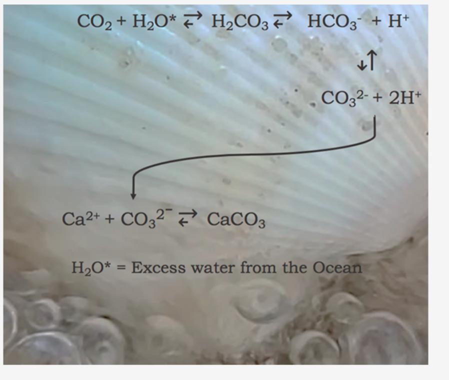
ABSTRACT: Students often experience difficulty in connecting knowledge from different college courses to solve complex problems such as ocean acidification, a pressing concern within the ongoing climate crisis. Here, we introduce a multidisciplinary activity in which students use their chemistry knowledge of change and stability in chemical systems through Le Chatelier's principle and equilibrium of coupled reactions to explain the biological phenomenon of how changes in CO_2 concentrations can impact shelled organisms and ecosystems more broadly in the ocean. In this activity, we build on prior literature and emphasize Three-Dimensional Learning (3DL) to support students in developing a deeper understanding of this complex problem. This Ocean Acidification activity asks students to explain (1) the relationship between CO_2 concentration and ocean pH and (2) how and why changes in ocean pH could weaken shelled organisms. Among 136 students in a second-semester general chemistry course at a large institution, 93% were able to correctly predict the relationship between CO_2 and pH (chemistry-biology connection). Additionally, 43% of the students were able to then further apply this knowledge correctly to explain an unfamiliar situation in which the decreased pH could lead to less available carbonate ion for the shells (biological phenomenon). This result highlights that while some students were able to correctly explain the biological phenomenon and make meaningful connections, others would require additional in-class scaffolding and student-instructor interaction to be able to integrate their knowledge to explain this unfamiliar complex biological phenomenon. Implications for teaching and future implementations are also discussed.



KEYWORDS: *First-Year Undergraduate/General, Interdisciplinary/Multidisciplinary, Student-Centered Learning, Acids/Bases, Equilibrium*

A robust understanding of science is essential to solve problems in the real world. Thus, helping students see how different science disciplines come together to advance our general understanding of the world, explain a variety of phenomena, and find solutions to global issues is critical. The interdisciplinary nature of discoveries and advances in science make it essential for future scientists to be able to use and integrate their knowledge across disciplines. However, over the years, literature has shown that students at multiple levels across different disciplines have difficulties using and connecting their knowledge within and across disciplines.[1−3] A contributing factor to these difficulties is a lack of high-quality activities that give students the opportunity to connect knowledge from multiple disciplines (e.g., chemistry and biology). Both students and educators recognize the importance of interdisciplinary connections;[4] thus, there is a critical need to develop instructional materials to help fill this gap.

As part of a larger project,[5] we have created a series of multidisciplinary activities that prompt students to use their chemistry knowledge to explain various biological phenomena.[6−8] This paper presents one of these activities developed to support students using their chemistry knowledge of change and stability of chemical systems to explain how ocean acidification can impact the formation of shelled organisms. The development for all of these multidisciplinary activities was guided by the three dimensions outlined in the *Framework for K-12 Science Education*: core ideas (what we want students to know), cross-cutting concepts (tools, lenses, or bridges that help students explain disciplinary ideas[9]), and scientific practices (what we want students to do with their knowledge), referred to as Three-Dimensional Learning (3DL).[10] Instruc-

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Box 1: Summary of the Administered Ocean Acidification Activity and Sample Prompts

Eliciting Initial Ideas

Example Prompt from Slide 2

What do you know about acid-base reactions? Write 1-2 sentences.

Chemistry-Biology Connection

Summary of Informational Slides 3-6

Multi-step reactions can be written as one long chain of reactions as shown here:

Ocean Acidification Reaction (Rxn)

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 + H_2O \rightleftharpoons HCO_3^- + H_3O^+ + H_2O \rightleftharpoons CO_3^{2-} + H_3O^+ \text{ (Rxn. A\&B\&C)}$$

Summary of the Chemistry-Biology Connections Prompts in Slides 7-9

Use this applet[31] to identify and model how changes in CO_2 concentrations affect pH levels in the ocean and predict how increases in CO_2 impact the following reaction.

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 + H_2O \rightleftharpoons HCO_3^- + H_3O^+ + H_2O \rightleftharpoons CO_3^{2-} + H_3O^+ \text{ (Rxn. A\&B\&C)}$$

Using two pieces of evidence (pH changes and direction of reaction), **explain** how an increase in atmospheric CO_2 leads to changes in pH levels.

Biological Phenomenon

Summary of Informational Slides 10 & 11

While the absorption of CO_2 by the ocean limits the large amount of CO_2 in the atmosphere, this process has a major impact on marine life.

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 + H_2O \rightleftharpoons HCO_3^- + H_3O^+ + H_2O \rightleftharpoons CO_3^{2-} + H_3O^+ \text{ (Rxn. A\&B\&C)}$$

Summary of Biology Phenomenon Prompts in Slides 12 & 13

The mineral calcium carbonate ($CaCO_3$) is a fundamental building block of many organisms in forming their shells.

$$Ca^{2+} + CO_3^{2-} \rightleftharpoons CaCO_3$$

Reflecting on the position of equilibrium for this series of reactions (in the red box above), if the shells for corals, mollusks, and other shelled organisms are composed of $CaCO_3$, how would an increase of CO_2 affect the concentration of $CaCO_3$ and the shell formation of marine creatures?

Applet: King's Center for Visualization in Science. Surface Ocean pH Levels https://applets.kcvs.ca/OceanAcidification/oceanAcid.html (accessed Aug 30, 2021).

tional materials developed using this framework are meant to engage students in thinking deeply about using and applying their knowledge in new and unfamiliar situations, also known as knowledge-in-use.[11,12]

The topic of ocean acidification is an important aspect of the ongoing climate crisis and provides a relevant context to the students of interest (explained further below). A variety of educational resources to support building students' understanding of ocean acidification are available[13] including hands-on experiments,[14,15] in-class activities,[16] demonstrations,[17] simulations,[18,19] and writing assignments.[20] Several of these resources focus heavily on the mathematical relationship

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between pH levels and the concentration of carbon dioxide. In a recent commentary Stowe et al. called upon the community to reflect on what we are emphasizing and assessing in our courses, as it becomes a message to our students about what we value in our courses.[21] So instead with our Ocean Acidification activity, we intended to support students in using their knowledge of chemistry core ideas to explain a more complex and unfamiliar biological phenomenon in a more qualitative manner. Furthermore, the design of the activity was guided by the 3DL framework to create an experience that had the potential to engage students in the use of scientific practices, chemistry core ideas, and crosscutting concepts in order to explain a phenomenon. In designing this activity, our interest was to have students explain these processes at the introductory general chemistry level.

■ ACTIVITY DEVELOPMENT AND DESCRIPTION

This Ocean Acidification activity is one of seven activities developed to support students with integrating and using chemistry core ideas to explain biological phenomena.[6−8] Among the faculty members at our institution, ocean acidification was identified as a phenomenon of high value from a list of biology topics that require chemistry ideas to be explained due to the coastal location of the university of interest in the Southeastern United States. In addition, previous research has revealed the low awareness and understanding of ocean acidification among biology, chemistry, and biochemistry students in comparison to other science students.[22] Given the complexity of ocean acidification, we simplified the focus of the activity to the weakening of shelled organisms since this can be more directly predicted with the chemistry core idea of change and stability in chemical systems, a prominent topic of second-semester general chemistry. Based upon the content taught within second-semester general chemistry, we decided to focus on how the changes in concentration of CO_2 and thus in H_3O^+ affect the rate of the forward and reverse reactions that take place when CO_2 dissolves in the ocean. While concepts like Lewis acid−base mechanism, dissociation constant, and solubility could have further been integrated to explain the highly complex system of ocean acidification, students at this level are not likely to have the conceptual understanding and working mental capacity to be able to fully use and apply them properly within a single activity (discussed further below). Exploring all of these ideas would require creating a series of activities to reduce the students' cognitive load.

Thus, using a simplified version of evidence-centered design,[23] this activity was developed to have two main sections (Box 1) in which students were asked to use their understanding of change and stability in chemical systems to explain (1) the impact that changes in the concentration of carbon dioxide have on the pH of the ocean (Chemistry−Biology Connection) and (2) how these changes impact the crustacean shells (Biology Phenomenon). In addition to the questions within these sections, we incorporated questions that elicited students' prior knowledge about relevant chemistry concepts (i.e., acid−base reactions, Le Chatelier's principle, and equilibrium). Scaffolding in the form of informational slides was included throughout. As shown in Box 1, students are introduced as part of the activity to a long chain of coupled reactions that depicts the dissolution of CO_2 in the ocean. This long chain of reactions is shown after students are walked through each individual reaction in isolation and informed of the limitations of such models in showing how these reactions happen simultaneously and not as steps. We decided to have students use this long chain of reaction as model for several reasons: (1) ocean acidification reactions are typically portrayed as a long chain of reaction system;[24−28] (2) our students were familiar with coupled reactions in this format (see details about our students below); (3) showing reactions as individual steps can suggest that each reaction happens in isolation, which is a limiting and inaccurate depiction of what is happening at the molecular level; and last (4) introducing students to reactions in this format could have the potential to support those students who will go on to upper level chemistry or biochemistry courses and will further encounter long chain reactions.[29] Box 1 provides an overview of the activity, not showing the scaffolding students were provided throughout the activity. The Supporting Information presents the full administered Ocean Acidification Activity, the characterization of the activity using the 3D-LAP,[30] and Instructor Guide for the administered activity. The applet[31] used within this activity is also included in the Supporting Information.

■ IMPLEMENTATION DETAILS

As part of this study, the activity was implemented during the last week of the second semester of general chemistry (GC II) in Spring 2021 at a large, predominantly Hispanic-serving institution (HSI) in the Southeastern United States. It is important to note that this GC II course used a transformed chemistry curriculum known as *Chemistry, Life, the Universe and Everything* (CLUE)[32] which emphasizes chemistry core ideas and student engagement with the scientific practices. While the course is typically taught in-person and is student-centered, during the Spring 2021 semester, it was offered remotely via Zoom due to the COVID-19 pandemic. To maintain CLUE's active-style classroom in the remote environment, undergraduate learning assistants (LAs) assisted within breakout rooms on Zoom to facilitate student learning using group activities and small group discussions.

Students in this GC II course typically are given three large midterm exams and a final exam, but with the switch to a remote modality, the instructors instead assessed student understanding using five smaller checkpoint assessments. In this course, students are often asked to use their knowledge to explain a range of phenomena; therefore, as one of these phenomena, the Ocean Acidification activity was administered as an out-of-class authentic learning activity. This authentic learning activity was administered in three phases during the final week of the semester as an opportunity for students to apply their knowledge to a new and unfamiliar situation.

Prior to implementation of the activity, students are introduced to the concepts of acid−base reactions, equilibrium, and LeChatelier's principle. Furthermore, in the CLUE curriculum, ideas build throughout the curriculum through a learning progression. This is meant to support students' understanding of phenomena starting with simple systems such as the interaction of two atoms to more complex systems like coupled reactions. Thus, we decided to use the long chain of reactions depicting the dissolution of CO_2 in the ocean because of students' experience and familiarity with these types of reactions and scientists' usual portrayal of ocean acidification as a long complex system.[24−28]

In the first phase of implementing the activity, the instructor provided students with additional resources in their learning management system which included videos and articles about

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ocean acidification (presented in Supporting Information) a week prior to launching the activity. As part of this prior homework, students were expected to explore these resources, which were hidden once the activity began. The second phase consisted of the activity itself, and the students were told to *not* use outside resources while completing this activity. The activity was administered via *beSocratic*, a platform familiar to the students that presents questions and information on slides where students can write and draw responses.[33] Additionally, students cannot go back to previous slides, which was essential to support the scaffolded nature of the activity; scientifically accurate information was revealed subsequently after students made their own initial predictions and explanations. The third, and final, phase was on Zoom where students were placed in breakout rooms with their learning assistants facilitating follow-up discussion regarding the completed activity. Students were asked to discuss this phenomenon and how they could apply what they learned in their general chemistry courses and other courses to explain this phenomenon as a group. This was followed by a whole class discussion on Zoom facilitated by the instructor.

A total of 136 students out of 186 enrolled in the course completed the activity and thus are included in the analyses below. Similar to previous activities and homework assignments done in this course, students were given credit for participating and completing the activity. For the purpose of this paper, students' responses were evaluated in terms of accuracy and examples of the expected responses were included in the Instructor's Guide found in the Supporting Information. In addition, the student examples presented in this paper were assigned pseudonyms to protect their identity.

■ STUDENT WORK AND DISCUSSION

Students' Use of Chemistry Knowledge to Explain a Biological Phenomenon

In the Chemistry−Biology Connection section (Box 1), 93% (n = 126) of the students correctly predicted that an increase in the dissolution of atmospheric CO_2 concentrations would result in decreased ocean pH (slide 8 from Administered Activity in the Supporting Information). That is, students were able to identify the relationship between the concentration of CO_2 and pH, which is the first step in the process of explaining the cause of ocean acidification. Furthermore, a similar number (88%, n = 120, slide 9 in the Supporting Information) of students were able to correctly predict how the increase in CO_2 impacted the equilibrium reaction of the CO_2 dissolution. These students were able to recognize that there would be an increase in the rate of the forward reaction and, therefore, there would be an increase in the concentration of products formed. This second step is essential in helping students understand the impact that atmospheric carbon dioxide has on the ocean, as previous research has shown that students are less familiar with this topic and hold a number of scientifically inaccurate ideas on the cause of ocean acidification.[22]

While it was encouraging to see that a large number of students were able to correctly identify the given relationship, we also observed students struggling to integrate their knowledge of acid−base reactions and equilibrium to make sense of the unfamiliar biological phenomenon at hand. After being asked to make a prediction about how adding CO_2 would impact the reaction, the students were provided with an informational slide (slide 11, in the Supporting Information) for the purpose of making sense of how the rates of these reactions would be affected and the equilibrium of the overall reaction would be re-established. However, results presented in Figure 1 show that when students were asked to predict how

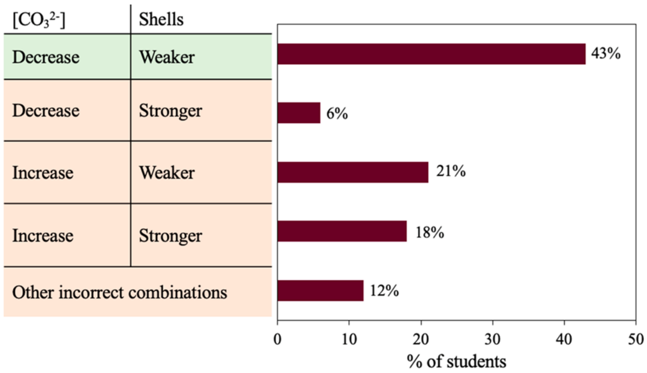

Figure 1. Student responses to how CO_2 concentration affects the amount of CO_3^{2-} and shelled organisms.

the concentration of CO_3^{2-} and consequently shell formation is affected by an increase in the dissolution of CO_2, only 43% (n = 59) identified the correct relationship. From these students, their explanations typically focused on the increase in the presence of hydronium ions from the slightly acidified ocean as explained by

Teresa: "*The free carbonate ions begin to react with the hydronium ions which therefore decreases the concentration of carbonate and increases the concentration of bicarbonate. Because there is a lower concentration of carbonate, there is less carbonate to react with calcium which would result in the formation of weaker shells.*"

Earnest: "*Due to there being less CO_3^{2-} ions present due to the increased interaction with the excess hydronium ions to form bicarbonate ions to fulfill an equilibrium; less carbonate ions would be available to create calcium carbonate and thus directly affect shelled marine creatures as their needed minerals become diminished. The less hydronium ions in the water, the more calcium carbonate that would be available and thus increasing the strength of these shelled creatures shells.*

Students like Teresa and Earnest had an accurate understanding of how an increase in the rate of the forward reaction (Rxn A and B and C) at equilibrium would be re-established by an increase in the rate of the reverse reaction forming HCO_3^- and thus reducing the amount of CO_3^{2-} available to produce $CaCO_3$. On the other hand, students who predicted that the ocean acidification would *increase* the amount of CO_3^{2-} and thus lead to *stronger* shells appear to have an incorrect understanding of what was labeled as the "equilibrium position" for the coupled reactions. For instance, consider the following student responses:

Miranda: "*The concentration of $CaCO_3$will increase because more reactants are present which will cause more product's making the shells stronger.*"

Jacquia: "*Because of higher reactants leading to more products.*"

Mateusz: "*If CO_2which is a reactant is increased, the concentration of $CaCO_3$would then be increased as well, resulting in the forward reaction being favored. This would then increase the strength of the shells since they are made up of the $CaCO_3$, and if there is a higher concentration of the $CaCO_3$, I would assume that it would made the shell stronger.*"

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These responses are indicative of the incorrect thinking that the equilibrium position for the coupled reactions is with CO_3^{2-} and H^+, instead of in the middle of the coupled reaction series (HCO_3^-, H_2O, H^+). While it was discouraging to see the number of students who were not able to integrate their knowledge, it is not surprising that students struggled with making sense of the reaction equilibrium as previous research has reported the difficulties students have with understanding the dynamic and reversible characteristic of equilibrium reactions.[34,35] Furthermore, while assessments like this Three-Dimensional activity have the potential to support students in the use and application of knowledge and skills, given that they are expected to integrate their knowledge in a coherent matter to predict and explain unfamiliar and highly complex systems/phenomena like the one presented here and in other types of assessments (i.e., chemical system thinking,[36] knowledge-in-use,[12] and phenomenon-based[37]), it is not unexpected that students would struggle and find these tasks challenging to complete. Thus, when presenting activities like Ocean Acidification, it is essential for the instructor to provide scaffolding throughout the activity and necessary support students might need to meet the goals of such assessments.

For example, prior to the implementation of this activity, it is important that instructors introduce students to the idea of multistep equilibria. Research on students' ideas about chemistry equilibrium has shown that students believe that (1) the forward and reverse reactions alternate and are distinct events and (2) equilibrium reactions go to completion before the reverse reaction begins.[38−40] By introducing students to these types of multistep reactions, we could potentially reduce the level of complexity associated with multistep equilibrium reactions and focus on the dynamic and reversible nature of the reaction being presented.

Instructors could also provide further post-administration prompting to help students think about where the equilibrium position would be for the coupled reactions and how excess H^+ would react with CO_3^{2-} and how the rate of the reverse reaction would increase to re-establish the equilibrium of the system (see Instructor's Guide in the Supporting Information). For example, in the third phase of this activity, the class meeting following the completion of the Ocean Acidification activity, students went into their Zoom breakout room and were asked to engage in a conversation regarding the impact of ocean acidification on marine organisms. After participating in small group discussions, the instructor facilitated a whole class discussion addressing students' alternative conceptions about ocean acidification. This discussion was followed up with having students discuss a set of solutions on how as a community we can decrease the production of CO_2 and thus combat ocean acidification and how they can contribute to this individually. The follow-up discussion and student feedback allowed the instructor to assess student understanding of the concepts involved in ocean acidification as well as their ability to make connections to the course content and think about how to modify future implementation of the activity by providing additional scaffolding in places where students needed additional assistance (see Modified Activity in the Supporting Information). It also showcased the importance of authentic learning and having students experience the process of making these connections which are relevant to the real world when they are learning the course content. Students need to be explicitly provided with multiple opportunities to use and apply their knowledge to explain new and unfamiliar systems and phenomena. Engaging productively in these types of activities will require time and a space to practice using and applying knowledge without negative consequences (i.e., where they are not penalized for making incorrect predictions or reasoning).

Student Familiarity and Confidence with Relevant Topics

Students were asked at the end of the activity to report their familiarity and confidence associated with the relevant topics. Students were also asked to provide feedback about the activity to aid future implementations. Data presented in Figure 2A

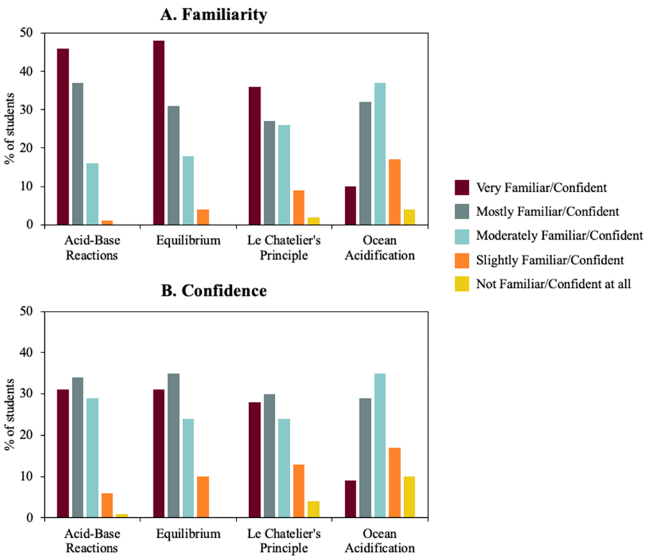

Figure 2. Self-reported student (A) familiarity and (B) confidence data on the four topics covered in the Ocean Acidification activity.

shows that over three-fourths of these chemistry students were either very familiar or mostly familiar with acid−base reactions (81%) and equilibrium (79%), less familiar with Le Chatelier's principle (63% familiar or mostly familiar), and even less familiar with ocean acidification (42% familiar or mostly familiar). Given their familiarity with the chemistry content knowledge needed to answer the questions presented, we would expect students to be able to use those ideas to explain the less familiar topic of ocean acidification. When comparing students' familiarity to their confidence (Figure 2B) about their knowledge of the same topics, many students stated being "mostly" and "moderately confident" about these. Such findings suggest that while students were familiar with the topics, they were not sure about their ability to use and apply this knowledge. As previously discussed, to support students in the use of their knowledge and boost their confidence in their ability to apply their knowledge, they need to be provided with more opportunities to explain new and unfamiliar phenomena.

Students' Feedback

Students' feedback about this activity was compiled into the word cloud in Figure 3 to identify trends in responses. Students provided many pieces of positive feedback about the activity, frequently using words such as "clear," "real," "enjoyed," and "interesting" to list a few. Specific student feedback included:

Cristina: "*I think the activity was great and it was a great connection between real life and the concepts learned in class.*"

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Figure 3. Word cloud of students' feedback to the Ocean Acidification activity.

Alex: "*This activity made me engage my brain and relate topics I have learned to everyday scenarios.*"

Additionally, some students shared more specific positive feedback about being asked to make connections between chemistry and biology. For example, Preston shared: "*This activity enhanced my knowledge on ocean acidification. I wasn't aware of how acid base reactions were a part of ocean processes and how it also affected shells.*"

While negative feedback from students was infrequent, the main point students raised regarded "visuals", as explained by these students:

Daniela: "*I think some visuals would help more. For me personally, being able to visually see it makes me comprehend the concepts better. Sometimes imagining it leads to me not fully grasping the content so a visual would help a lot.*"

Izzie: "*Diagrams would have also been more visually appealing.*"

Based on this feedback, future iterations of this activity could include visuals such as atomic-molecular diagrams of the reactions involved (instead of just symbolic representations) and more diagrams or figures of the equilibrium process and how marine creatures use CO_3^{2-} to create their shells. For example, the equilibrium arrows could be further represented to show directionality for each reaction (see Modified Activity in the Supporting Information). In addition, while students in this course had been previously introduced to coupled reactions similar to those presented in the activity in the format of a long chain of reactions, this may not typically be introduced in some traditional chemistry curricula. Refer to the Supporting Information for Suggested Modifications to the activity.

Alternative Directions for the Activity

Unfortunately, many examples of real-world systems tend to be too complex for students taking an introductory chemistry class to explain in detail which can leave students more confused as a result. As presented, students were expected to provide a reasonable explanation of ocean acidification using a *qualitative* interpretation of the acid−base reactions and their understanding of equilibrium as well as Le Chatelier's principle, which would lead students to provide a simple rationale to a very complex system. Alternatively, instructors could consider incorporating a *quantitative interpretation* of the system by including data, such as acid dissociation constants (or pK_a) for H_2CO_3 as well as the solubility products of $CaCO_3$ along with a more in-depth discussion of the relative equilibrium position. The addition of these data would require students to have a thorough understanding of what these values mean and how to incorporate those into their explanation of ocean acidification, otherwise this could lead to major student difficulties and confusion. If the desired goal becomes for students to apply their knowledge of pK_a into this activity, then a series of activities would be helpful to minimize the cognitive demand of the students within a single activity. For example, the first activity could be dedicated to predicting and explaining the relationship between pK_a values and equilibrium position within coupled reactions. This newly designed activity could then be followed up with a second activity having students apply their knowledge from the first activity to the biological phenomenon presented within this Ocean Acidification Activity. Other future directions could include a post activity exploration in which students are given a list of factors (e.g., temperature, location, pressure, depth of the ocean) that potentially contribute to ocean acidification and shell formation to investigate how each of these parameters impact pH levels in the ocean, especially if a more robust systems thinking understanding is desired.

■ SUMMARY, IMPLICATIONS FOR TEACHING, AND LIMITATIONS

The student feedback obtained from this activity highlights how students want and appreciate connections between their knowledge learned within the course and the real world. However, most "real-world" problems are cross-disciplinary, and students often struggle with making connections across disciplines. The results from this activity highlight how students are trying to apply their chemistry knowledge to the biological scenario of ocean acidification, an unfamiliar situation to students even after completing multiple semesters of biology or environmental studies. In our Ocean Acidification activity, 93% were able to correctly predict the relationship between CO_2 and pH, with 43% of students further making the correct prediction regarding how changes in the pH of the ocean could affect shelled organism. These results are similar to the implementation and evaluation of previously developed multidisciplinary activities, where we found that in general (1) students found the activities useful to connect ideas and disciplines they would not have otherwise, and (2) while many students could provide sophisticated responses that incorporated their understanding of chemistry ideas to explain the chemistry phenomena, they had difficulties using the same ideas to explain biological phenomena.[6−8] Thus, previous[6−8,12] and current work highlights the importance of supporting students through the use of knowledge by providing them with experiences similar to the one presented in this study. Even, if students struggle to make the desired connections, we need to provide them with such opportunities to grow and learn. As part of the Supporting Information, we have included suggestions on how to further guide students through this activity (see potential guiding discussion questions in Supporting Information Instructor's Guide).

As instructors, if we want our students to form in-depth and useful understanding of their science knowledge, they must be given the opportunities to practice integrating and making connections within and across disciplines. For example, after being formally introduced to the concepts of acid−base equilibrium, students could be presented with activities similar to the one presented herein. In addition to providing students with explicit opportunities to form connections between their science knowledge, it is essential that instructors dedicate time to support the formation of such connections. In this case, it would be helpful to hold a post-implementation discussion where instructors have the opportunity to gauge students' ideas about the dynamic nature of reactions and how they applied their knowledge to explain ocean acidification. While we observed that there is still work to be done in order to help students integrate their knowledge, the Ocean Acidification activity has the potential to provide that support. As part of our findings, we present a modified version of the Ocean Acidification in the Supporting Information to further support future implementations of this activity. Some of the modifications include: (1) the addition of equilibrium arrows that depict directionality for each set of reactions; (2) it has been noted that H_2O is in excess and while it participates in every reaction step it is not shown for simplicity; and (3) similarly H_3O^+ was replaced with H^+ to represent a more accurate model of the nature of a solvated proton[41,42] and reduce cognitive load when students interact with the equations.

Finally, the activity and results presented here are limited in that students completing the activity were in a remote modality and were using a transformed general chemistry curriculum that emphasizes core chemistry ideas and supports students' conceptual understanding rather than quantitative analysis. In addition, students within the CLUE curriculum are familiar with coupled reactions, which may not be typical for other institutions. Hence, students may need additional scaffolding to better help support them if this is the case. It is unknown how students using a more traditional curriculum and an in-class modality would perform on this activity. For this reason, we have included an instructor's guide in the Supporting Information to help instructors in the administration and evaluation of this activity outside of our institution.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00981.

Administered Ocean Acidification Activity, Instructor's Guide to the Ocean Acidification Activity, Resources About Ocean Acidification, Characterization of the Ocean Acidification Activity using the 3D-LAP, and Suggested Modifications to the Ocean Acidification Activity (PDF, DOCX)

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Notes

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■ REFERENCES

(1) Kohn, K. P.; Underwood, S. M.; Cooper, M. M. Connecting Structure – Property and Structure – Function Relationships across the Disciplines of Chemistry and Biology: Exploring Student Perceptions. *CBE Life Sci. Educ.* **2018**, *17* (2), ar33.

(2) Kohn, K. P.; Underwood, S. M.; Cooper, M. M. Energy Connections and Misconnections across Chemistry and Biology. *CBE Life Sci. Educ.* **2018**, *17* (1), ar3.

(3) Wright, A.; Provost, J.; Roecklein-Canfield, J. A.; Bell, E. Essential Concepts and Underlying Theories from Physics, Chemistry, and Mathematics for "Biochemistry and Molecular Biology" Majors. *Biochem. Mol. Biol. Educ.* **2013**, *41* (5), 302–308.

(4) American Association for the Advancement of Science. *Vision and Change in Undergraduate Biology Education: A Call to Action*; AAAS: Washington, DC, 2011.

(5) Matz, R. L.; Underwood, S. M.; Parent, K. N. A Three-Dimensional Approach to Connecting Biology & Chemistry. *Scientia* **2019**, DOI: 10.26320/scientia310.

(6) Roche Allred, Z. D.; Farias, A. J.; Kararo, A. T.; Parent, K. N.; Matz, R. L.; Underwood, S. M. Students' Use of Chemistry Core Ideas to Explain the Structure and Stability of DNA. *Biochem. Mol. Biol. Educ.* **2021**, *49*, 55–68.

(7) Martinez, B. L.; Kararo, A. T.; Parent, K. N.; Underwood, S. M.; Matz, R. L. Creating and Testing an Activity with Interdisciplinary

Connections: Entropy to Osmosis. *Chem. Educ. Res. Pract.* **2021**, *22* (3), 683−696.
(8) Green, A. I.; Parent, K. N.; Underwood, S. M.; Matz, R. L. Connecting Ideas Across Courses: Relating Energy, Bonds and How ATP Hydrolysis Powers a Molecular Motor. *Am. Biol. Teach.* **2021**, *83* (5), 303−310.
(9) Cooper, M. M. The Crosscutting Concepts: Critical Component or "Third Wheel" of Three-Dimensional Learning? *J. Chem. Educ.* **2020**, *97*, 903.
(10) National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; The National Academies Press: Washington, DC, 2012.
(11) Harris, C. J.; Krajcik, J. S.; Pellegrino, J. W.; Mcelhaney, K. W.; Debarger, A. H.; Dahsah, C.; Damelin, D.; D 'angelo, C. M.; Dibello, L. V.; Gane, B.; et al. *Constructing Assessment Tasks That Blend Disciplinary Core Ideas, Crosscutting Concepts, and Science Practices for Classroom Formative Applications Center for Technology in Learning*; SRI International: Menlo Park, CA, 2016.
(12) Harris, C. J.; Krajcik, J. S.; Pellegrino, J. W.; Debarger, A. H. Designing Knowledge-In-Use Assessments to Promote Deeper Learning. *Educational Measurement: Issues and Practices* **2019**, *38* (2), 53−67.
(13) Fauville, G.; Säljö, R.; Dupont, S. Impact of Ocean Acidification on Marine Ecosystems: Educational Challenges and Innovations. *Mar. Biol.* **2013**, *160* (8), 1863−1874.
(14) Perera, A. P.; Bopegedera, A. M. R. P. Laboratory Experiment Investigating the Impact of Ocean Acidification on Calcareous Organisms. *J. Chem. Educ.* **2014**, *91* (11), 1951−1953.
(15) Buth, J. M. Ocean Acidification: Investigation and Presentation of the Effects of Elevated Carbon Dioxide Levels on Seawater Chemistry and Calcareous Organisms. *J. Chem. Educ.* **2016**, *93* (4), 718−721.
(16) Bozlee, B. J.; Janebo, M.; Jahn, G. A Simplified Model To Predict the Effect of Increasing Atmospheric CO2 on Carbonate Chemistry in the Ocean. *J. Chem. Educ.* **2008**, *85* (2), 213.
(17) Finkenstaedt-Quinn, S. A.; Hudson-Smith, N. V.; Styles, M. J.; Maudal, M. K.; Juelfs, A. R.; Haynes, C. L. Expanding the Educational Toolset for Chemistry Outreach: Providing a Chemical View of Climate Change through Hands-on Activities and Demonstrations Supplemented with TED-Ed Videos. *J. Chem. Educ.* **2018**, *95* (6), 985−990.
(18) Towns, M.; Kirchhoff, M.; Mahaffy, P.; Martin, B. *Acids & Bases*. http://www.vc3chem.com/ (accessed 2021-08-23).
(19) McKenzie, L.; Versprille, A.; Towns, M.; Mahaffy, P.; Martin, B.; Kirchhoff, M. *Visualizing the Chemistry of Climate Change (VC3Chem): Online Resources for Teaching and Learning Chemistry through the Rich Context of Climate Science*; American Physical Union, Fall Meeting 2013; 2013; Vol. *2013*, abstract id ED31E-04. ui.adsabs.harvard.edu.
(20) Moon, A.; Moeller, R.; Gere, A. R.; Shultz, G. V. Application and Testing of a Framework for Characterizing the Quality of Scientific Reasoning in Chemistry Students' Writing on Ocean Acidification. *Chemistry Education Research and Practice* **2019**, *20* (3), 484−494.
(21) Stowe, R. L.; Scharlott, L. J.; Ralph, V. R.; Becker, N. M.; Cooper, M. M. You Are What You Assess: The Case for Emphasizing Chemistry on Chemistry Assessments. *J. Chem. Educ.* **2021**, *98* (8), 2490−2495.
(22) Danielson, K. I.; Tanner, K. D. Investigating Undergraduate Science Students' Conceptions and Misconceptions of Ocean Acidification. *CBE Life Sci. Educ.* **2015**, *14* (3), ar29.
(23) Mislevy, R. J.; Haertel, G. D. Implications of Evidence-Centered Design for Educational Testing. *Educational Measurement: Issues and Practice* **2006**, *25* (4), 6−20.
(24) Hönisch, B.; Ridgwell, A.; Schmidt, D. N.; Thomas, E.; Gibbs, S. J.; Sluijs, A.; Zeebe, R.; Kump, L.; Martindale, R. C.; Greene, S. E.; et al. The Geological Record of Ocean Acidification. *Science* **2012**, *335* (6072), 1058−1063.
(25) Ocean Acidification: Acting on Evidence. In *Messages for Rio +20*; Laffoley, D. D., Baxter, J. M., Eds.; European Project on Ocean Acidification (EPOCA), UK Ocean Acidification Research Program (UKOA), Biological Impacts of Ocean Acidification (BIOACID), and Mediterranean Sea Acidification in a Changing Climate (MedSeA), 2011; p 8.
(26) Barker, S.; Ridgwell, A. Ocean Acidification. *Nat. Educ. Knowl.* **2012**, *3* (10), 21.
(27) Overview of Ocean and Coastal Acidification. http://www.necan.org/overview (accessed 2022-02-07).
(28) What is Ocean Acidification? https://usa.oceana.org/what-ocean-acidification/ (accessed 2022-02-07).
(29) Voet, D.; Voet, J. G. *Biochemistry*, 4th ed.; John Wiley & Sons, Inc: Hoboken, NJ, 2011; p 386.
(30) Laverty, J. T.; Underwood, S. M.; Matz, R. L.; Posey, L. A.; Carmel, J. H.; Caballero, M. D.; Fata-Hartley, C. L.; Ebert-May, D.; Jardeleza, S. E.; Cooper, M. M. Characterizing College Science Assessments: The Three-Dimensional Learning Assessment Protocol. *PLoS One* **2016**, *11* (9), e0162333.
(31) *Surface Ocean pH Levels*; King's Center for Visualization in Science. https://applets.kcvs.ca/OceanAcidification/oceanAcid.html (accessed Aug 30, 2021).
(32) Cooper, M. M.; Klymkowsky, M. Chemistry, Life, the Universe, and Everything: A New Approach to General Chemistry, and a Model for Curriculum Reform. *J. Chem. Educ.* **2013**, *90* (9), 1116−1122.
(33) Cooper, M. M.; Underwood, S. M.; Bryfczynski, S. P.; Klymkowsky, M. W. A Short History of the Use of Technology to Model and Analyze Student Data for Teaching and Research. In *Tools of Chemistry Education Research*; Cole, R., Bunce, D. M., Eds.; American Chemical Society: Washington, DC, 2014; pp 219−239.
(34) Bergquist, W.; Heikkinen, H. Student Ideas Regarding Chemical Equilibrium: What Written Test Answers Do Not Reveal. *J. Chem. Educ.* **1990**, *67* (12), 1000.
(35) Tyson, L.; Treagust, D. F.; Bucat, R. B. The Complexity of Teaching and Learning Chemical Equilibrium. *J. Chem. Educ.* **1999**, *76* (4), 554.
(36) Talanquer, V. Some Insights into Assessing Chemical Systems Thinking. *J. Chem. Educ.* **2019**, *96* (12), 2918−2925.
(37) Penuel, W. R.; Turner, M. L.; Jacobs, J. K.; Horne, K.; Sumner, T. Developing Tasks to Assess Phenomenon-based Science Learning: Challenges and Lessons Learned from Building Proximal Transfer Tasks. *Sci. Educ.* **2019**, *103*, 1367.
(38) Andriani, Y.; Mulyani, S.; Wiji, W. Misconceptions and Troublesome Knowledge on Chemical Equilibrium. *J. Phys. Conf. Ser.* **2021**, *1806* (1), 012184.
(39) Aini, F. Q.; Fitriza, Z.; Gazali, F.; Mawardi. First-Year University Students' Understanding of Chemical Equilibrium. *J. Phys. Conf. Ser.* **2019**, *1280*, 032018.
(40) Satriana, T.; Yamtinah, S.; Ashadi; Indriyanti, N. Y. Student's Profile of Misconception in Chemical Equilibrium. *J. Phys. Conf. Ser.* **2018**, *1097*, 012066.
(41) Stoyanov, E. S.; Stoyanova, I. V.; Reed, C. A. The Unique Nature of H+in Water. *Chem. Sci.* **2011**, *2* (3), 462−472.
(42) Silverstein, T. P. The Aqueous Proton Is Hydrated by More Than One Water Molecule: Is the Hydronium Ion a Useful Conceit? *J. Chem. Educ.* **2014**, *91* (4), 608−610.

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