Connecting Ideas across Courses: Relating Energy, Bonds & How ATP Hydrolysis Powers a Molecular Motor

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ABSTRACT
Core chemistry ideas can be useful tools for explaining biological phenomena, but students often have difficulty understanding these core ideas within general chemistry. Connecting these ideas to biologically relevant situations is even more difficult. These difficulties arise, in part, from a lack of explicit opportunities in relevant courses for students to practice connecting ideas across disciplines. We are developing activities that examine students’ abilities to connect core chemistry ideas with biological phenomena, the overall goal being to develop a set of assessments that ask students to connect their knowledge across introductory chemistry and biology courses. Here, we describe the development and testing of an activity that focuses on concepts about energy in bond breaking, bond forming, and ATP coupling. The activity was completed by 195 students in an introductory cell and molecular biology course at Michigan State University; students were either co-enrolled or previously enrolled in General Chemistry I. Follow-up interviews to assess the validity of the activity (among others) showed that students interpreted the questions as intended and that they valued the activity as an opportunity to connect ideas across courses.

Key Words: assessment; biology education; college teaching; energy; science practices.

Introduction
Experts agree that helping students learn to connect ideas across science disciplines is important: “[Students] must possess enough knowledge about related disciplines … to bring the requisite expertise to address complex issues” (AAAS, 2011). Yet designing learning environments that support students in making such connections is difficult, especially at the secondary and postsecondary levels, where disciplines and faculty are typically compartmentalized by department. Students struggle to make interdisciplinary connections (Mil et al., 2016), particularly with respect to complicated topics like energy (Kohn et al., 2018; Opitz et al., 2019). Perhaps more important than identifying the difficulties students have in connecting ideas across disciplines is working to develop and test curricular materials that provide opportunities for students to make such connections (Sibanda & Hobden, 2015), going beyond existing science assessments that often encourage rote memorization and assess factual recall (Momsen et al., 2010).

We are developing activities (Matz et al., 2019; Roche Allred et al., 2021) that provide opportunities for students to connect ideas across two disciplines at the undergraduate level: general chemistry and introductory cell and molecular biology. These disciplines are of interest for at least two reasons. First, life science students tend to comprise a substantial portion of the overall student body seeking science, technology, engineering, and mathematics degrees (Chen, 2013), and essentially all of these students will take courses in both introductory cell and molecular biology and general chemistry. Second, creating opportunities for students to integrate their knowledge across biology and chemistry is a ripe area for development (Haudek et al., 2012), given the wide range of concepts with utility in both biology and chemistry (e.g., reduction-oxidation reactions, equilibrium, and free energy). The goal of our overall project is to address the following research question: In what ways do students use their chemistry knowledge to explain biological phenomena? Here, we report on the design and implementation of a specific activity that asks students to connect ideas about energy, covalent bonds, and adenosine triphosphate (ATP) hydrolysis in the context of a molecular bacteriophage motor.

We employ a constructivist paradigm (Ertmer & Newby, 1993) for the activity design, which emphasizes students developing knowledge that is useful to explain a phenomenon or solve a problem within a given context. We also rely heavily on three-dimensional learning from A Framework for K–12 Science Education (hereafter Framework; National Research Council, 2012) for grounding this work, integrating scientific practices, disciplinary core ideas, and crosscutting concepts in each activity. We have argued that the Framework can be readily applied to the college level (Cooper et al., 2015; Laverty et al., 2016; Bain et al., 2020) and that it provides a useful basis for implementing and evaluating changes in both instruction and assessment in introductory undergraduate science courses (Matz et al., 2018; Underwood et al., 2018). Additionally, emphasizing scientific practices, disciplinary core ideas, and cross-cutting concepts as described in the Framework and subsequent
Next Generation Science Standards (NGSS) at the college level can provide continuity for students between K–12 and postsecondary science instruction (National Research Council, 2013).

Scholars who focus on creating NGSS-aligned assessments for the K–12 level have described the inherent difficulties in designing and evaluating such assessments – for example, the need for “clear guidance on how to assess the knowledge and skills associated with the standards” (Harris et al., 2019) as well as the “limited number of good examples” for proximal transfer tasks (Penuel et al., 2019). While developing assessments that elicit knowledge-in-use and support student learning is difficult at every level (Shepard, 2000), these problems are even more pronounced at the postsecondary level, where three-dimensional assessment design is totally nascent and faculty resources for developing such items are few and far between (Underwood et al., 2018). Thus, while we used the student responses to the activity presented here to understand more about how students connect their ideas across disciplines, our primary goal in this work was the development of the activity itself to support student engagement with interdisciplinary three-dimensional learning at the college level.

Methods

Context

This study was conducted at Michigan State University (MSU), a large four-year public university with high undergraduate enrollment and very high research activity (Carnegie Classifications of Institutions of Higher Education, n.d.). The study was exempted from review by MSU’s Human Research Protection Program (no. 00000430). After an in-depth review of the curricula in the relevant general chemistry and cell and molecular biology courses, we developed 11 “areas of connection” between the disciplines that could be probed for assessment development in our specific context. We surveyed MSU’s introductory biology instructors (N = 15, excluding coauthor K.N.P.) about which areas of connection with general chemistry they prioritized most highly. We specifically surveyed the biology instructors because MSU students typically take General Chemistry I before introductory biology and thus, at this institution, they would generally need to be enrolled in biology to begin making connections between the disciplines. The instructors were asked to rank each of the 11 areas of connection as being of “high,” “low,” or “no” value for the purpose of prioritizing which would first be developed into activities. The connection between energy, covalent bonds, and ATP hydrolysis was ranked as “high value” by all of the 11 instructors who responded to the survey.

Activity Design

The two-page written activity (Appendix S1) specific to this study focuses on connections between the role of energy in bond breaking and forming and how ATP hydrolysis facilitates the packaging of DNA into a bacteriophage capsid (Liu et al., 2014). The activity consists of two main sections and took students ~20 minutes to complete individually. Alignment between the activity sections and the Framework dimensions of core ideas, scientific practices, and crosscutting concepts is provided in Appendix S2. Both appendices are available as Supplemental Material with the online version of this article.

Section One (Q1–3). The first section asks students to recall information about the role of energy in bond breaking and forming – specifically that energy is required to break covalent bonds, and energy is released when bonds are formed – as well as to describe what they know about how ATP is used to support cellular functions. Students are then asked to connect their knowledge about bond breaking and forming to a symbolic representation of ATP hydrolysis and explain a corresponding reaction coordinate diagram.

Section Two (Q4–6). The second section is a scaffolded series of questions that asks students to link their ideas about energy and ATP interactions to the process of DNA packaging into a bacteriophage, visualized with a short video of the phenomenon (Saville, 2011). The last questions ask students to describe what happens to the protein subunits when ATP is hydrolyzed and why the physical interactions between ATP and the motor are important, offering an opportunity to connect ideas about how energy released from ATP hydrolysis can be useful in a specific biological process.

Data Collection

The activity was given to one course section of the introductory Cell and Molecular Biology course during both the fall 2018 (N = 140) and fall 2019 (N = 149) semesters as an optional take-home assignment for a nominal amount of extra credit points. Both course sections were co-taught by the same two instructors. The activity was administered in the middle of the semester as part of a unit on cellular respiration. During a specific class meeting, students had some brief preparatory instruction specifically on ATP coupling, viewed the video together, and engaged in a short discussion; the completed activity was due at the beginning of the next class meeting. The student responses in 2018 (n = 110; 79%) and 2019 (n = 100, 67%) were collected, organized, and scanned for analysis. Seven students in 2018 and eight students in 2019 turned in but did not complete the entire activity and were removed from the pool of responses, leaving a total of 195 student responses for these analyses.

Data Analysis

A coding scheme with four categories (Table 1) was developed through an iterative process of identifying patterns in student responses and checking these themes against new data (Ryan & Bernard, 2003). Two questions (Q1 and Q3) from the first section of the activity were analyzed for how the students described the roles of energy in breaking and forming covalent bonds; students had multiple opportunities across these two questions (including subparts) to discuss energy and bonding. Five codes were identified for this category of the coding scheme, ranging from fully correct (i.e., stating both that energy is required to break bonds and that energy is released when bonds are formed) to mixed, partially correct statements, to fully incorrect ideas. We coded student responses holistically across both Q1 and Q3. That is, students had to respond correctly across both questions consistently – thus demonstrating stability of ideas from one question to the next – for their responses to be coded as “Correct.”

The last question (Q6) in the second section of the activity asks what happens to the protein subunit when ATP is hydrolyzed (part d) and why the physical interactions between ATP and the motor are important (part e), prompting students to connect their ideas about energy and ATP interactions to the biological phenomenon of DNA packaging in the bacteriophage. Student responses were coded across three categories, each with various possible codes. The first category related to how the process was initiated (through the energy released from bond formation during ATP
The coding scheme was developed by two coders independently rating student responses, meeting to reconcile, and adjusting the coding scheme accordingly. Once the coding scheme was stable, inter-rater reliability was established between the two coders using a subset of 23 responses and the Gwet's AC1 coefficient (ranging from 0.74 to 0.85), which has been shown to be similar to, but more stable than, Cohen's kappa, especially under conditions of low prevalence (Wongpakaran et al., 2013). All remaining responses were then coded by a single coder. We made minor adjustments to the 2019 version of the activity to improve clarity for students, but these adjustments did not affect the coding scheme.

### Table 1. Summary of the coding scheme used to categorize student responses to the two-page written assignment (see text). The scheme consists of four categories, each with a unique set of codes. A brief description of each category and code along with a short, illustrative quote in italics is provided. The first category of coding (1. Bond breaking and forming) is based on student responses to Section One of the activity (Q1 and Q3), and the remaining three categories (2.1 Initiation, 2.2 Mechanism, and 2.3 Effect) are based on responses to Section Two (Q6d and Q6e).

| Category | Description | Illustrative Quote |
|----------|-------------|--------------------|
| 1. Bond breaking and forming: | Energy is required to break a bond and is released when a bond is formed. | Energy is released when bonds form but is needed when they are broken. |
| 1.1 Correct: | Students describe both roles of energy correctly. | Energy is released when bonds form but is needed when they are broken. |
| 1.2 Incomplete correct: | Students describe one role of energy correctly. | Energy is the role that breaks the bonds. |
| 1.3 Partial: | Students describe one role of energy correctly and one incorrectly. | It requires energy to break and form bonds. |
| 1.4 Incomplete incorrect: | Students describe one role of energy incorrectly. | Sometimes the creation of covalent bonds uses energy. |
| 1.5 Incorrect: | Students describe both roles of energy incorrectly. | Bond is formed, energy is absorbed, and when it is broken, energy is released. |
| 2.1. Initiation: | ATP hydrolysis provides the system with energy. | Energy is required for the DNA to be packaged and ATP hydrolysis has to be paired with packaging. |
| 2.1.1 ATP hydrolysis and energy: | Students describe hydrolysis as providing the energy. | Energy is required for the DNA to be packaged and ATP hydrolysis has to be paired with packaging. |
| 2.1.2 ATP interactions and energy: | Students describe ATP interactions and energy. | ATP physical interactions is the energy source. |
| 2.1.3 ATP and energy: | Students describe ATP and energy. | ATP is what provides energy. |
| 2.1.4 ATP or ATP interactions: | Students describe ATP or ATP interactions but not energy. | ATP helps move along the DNA. |
| 2.1.5 Other: | Students provide an unrelated response. | The shapes of each unit fit together nicely to function. |
| 2.1.6 Non-normative: | Students provide a nonscientific response. | They’re important because they must be able to connect and disconnect from one another. |
| 2.2 Mechanism: | The energy causes the shape of the protein to change. | The interactions cause the red pieces to change their shape. (Relevant parts of the protein are colored red in the video.) |
| 2.2.1 Protein changes shape: | Students describe the protein changing shape. | The interactions cause the red pieces to change their shape. (Relevant parts of the protein are colored red in the video.) |
| 2.2.2 Protein can move: | Students describe the protein moving but not specifically with respect to shape. | The physical interactions allow the protein subunit to move and package DNA. |
| 2.2.3 Protein only: | Students describe the protein but nothing with respect to movement. | The physical interactions are important because the protein is very big so it takes up a lot of space. |
| 2.2.4 Other: | Students provide an unrelated response. | The shape shows how it will interact with others. |
| 2.2.5 Non-normative: | Students provide a nonscientific response. | Because it needs to create a double helix structure. |
| 2.3 Effect: | The DNA is packaged within the bacteriophage. | The interactions provide the “fuel” needed to power this motor. |
| 2.3.1 DNA is packaged in bacteriophage: | Students describe DNA moving into the bacteriophage in a directional way. | Allowing for movement of the DNA strand down into the bacteriophage. |
| 2.3.2 DNA moves: | Students describe DNA moving but in a nondirectional way. | [...] gives the motor the energy it needs to package the DNA. |
| 2.3.3 Motor uses energy: | Students describe the system using energy. | [...] gives off energy to help power the motor. |
| 2.3.4 Motor is powered: | Students describe the motor being powered but without explicitly referencing energy. | The interactions provide the “fuel” needed to power this motor. |
| 2.3.5 Other: | Students provide an unrelated response. | If done wrong, the DNA packaging would fail. |
| 2.3.6 Non-normative: | Students provide a nonscientific response. | It can form a complex compound. |

hydrolysis); the second category related to the protein changing shape as a key mechanistic step in the process; and the third category related to the effect, that is, the DNA itself being packaged in the bacteriophage.

The coding scheme was developed by two coders independently rating student responses, meeting to reconcile, and adjusting the coding scheme accordingly. Once the coding scheme was stable, inter-rater reliability was established between the two coders using a subset of 23 responses and the Gwet’s AC1 coefficient (ranging from 0.74 to 0.85), which has been shown to be similar to, but more stable than, Cohen’s kappa, especially under conditions of low prevalence (Wongpakaran et al., 2013). All remaining responses were then coded by a single coder. We made minor adjustments to the 2019 version of the activity to improve clarity for students, but these adjustments did not affect the coding scheme.
Validity

The validity of the activity is supported by several efforts (Arjoon et al., 2013). First, beyond those on the research team, the activity was reviewed by experts in biochemistry education, chemistry education, and science education prior to being given to students. Second, at the end of the fall 2018 semester, we conducted one-hour cognitive interviews with seven students, incentivizing their participation with a $25 gift card. We probed for students’ thinking and reflection on each of the questions on the activity as well as on other activities that they had completed. The results of these interviews allowed us to (1) determine that the students largely understood and interpreted the language of the questions as intended, supporting the face validity of the activity for the larger student population (Bretz, 2014); and (2) make the minor adjustments previously mentioned for the fall 2019 administration.

Finally, while we were interested in supporting cross-disciplinary connections with this activity, we recognized that only a subset of students in the introductory Cell and Molecular Biology course would have recently taken the mainstream General Chemistry II course at MSU that covers energy and covalent bonding in terms of reaction chemistry. Other students were concurrently enrolled in this General Chemistry II course, had taken an alternate version (e.g., honors), had earned Advanced Placement or transfer credit, or were not required to take this course. Because of this unequal preparatory experience and the formative nature of this activity, we gave students the extra credit incentive based on their effort in completing the activity, not on correctness.

Thus, as a validity check as to whether students who completed the activity were taking it seriously and trying their best, we collected student responses to a specific General Chemistry II final exam question for the 46 students across both cohorts who had enrolled in the mainstream General Chemistry II course prior to their biology course in either fall 2018 or fall 2019. The vast majority of these students had enrolled in General Chemistry II in the prior spring semester. This straightforward, multiple-choice final exam question asked students about the role of energy during bond breaking and forming (Figure 1). Student responses were analyzed and compared to the responses from the first section of the activity, showing that similar numbers of students responded correctly to the final exam question (39/46 = 85%) as were coded with correct responses to Section One of the activity (36/46 = 78%).

Figure 1. Final exam question from General Chemistry II (asterisk indicates correct response).

Results & Discussion

The Role of Energy in Bond Breaking & Forming

In this activity, we first asked students to describe knowledge they had previously developed about the breaking and forming of covalent bonds. Students were then prompted to evaluate statements from two students (Jill and Jaime) who had made claims about aspects of ATP hydrolysis. Jill inaccurately claims that the oxygen-phosphate bond in ATP is a “high-energy bond” because energy is released when the bond is broken during hydrolysis. In contrast, Jaime claims that breaking the oxygen-phosphate bond would require energy. We asked students to explain their thinking about these two statements, consider a corresponding reaction coordinate diagram, and ultimately choose and justify which student they felt was more correct on the whole. Each student’s responses to these questions were coded (see Figure 2).

The vast majority (n = 99, 96%) of the 103 responses from 2018 showed that students readily have access to at least one correct idea about the role of energy in bond breaking and forming; that is, very few students gave an “incorrect” or “incomplete incorrect” response for this category. Similarly, 84 of the 92 students (91%) in 2019 replied with at least one correct idea. Overall, the distribution of responses in 2018 and 2019 are not statistically different (Mann-Whitney U = 4316, p = 0.24). This consistency of responses from one administration to the next provides evidence of test-retest reliability of the activity (Cooper et al., 2012; Arjoon et al., 2013),
given that the enrolled student population in this course is relatively consistent from year to year in terms of prior coursework as well as demographics.

The large percentage of students in both administrations (44% in 2018, 45% in 2019) who gave a “partial” response serves as another reminder about how challenging it is to help students develop and communicate a robust understanding of energy and bonding that remains consistent across a variety of questions and scenarios (Coope & Klymkowsky, 2013; Bain & Towns, 2018). Here, students had multiple opportunities within the first section of the activity to demonstrate their knowledge about bonds and energy, and we observed a wide range of responses. Among the 86 students across both cohorts whose responses were coded as “partial,” roughly equal numbers of students gave (a) more correct than incorrect responses or (b) more incorrect than correct responses (Table 2).

Here, we include some responses from students to help illustrate this range of ideas. Among the students who provided more correct than incorrect responses, we often saw statements similar to the following, from Kisha: “It takes a large amount of energy to break and form covalent bonds.” Despite describing the relationship between energy and covalent bonding correctly across the rest of the questions in Section One of the activity, Kisha incorrectly implies here that the formation of covalent bonds can require energy. Rashmi provided an interesting response illustrative of students who gave equal numbers of correct and incorrect responses. In describing the relationship between energy and bonding, she writes: “Energy is released when a bond is broken. Energy is absorbed when a bond is created. It takes energy to break a bond. Energy is released when a bond is formed.” As for Kisha, Rashmi’s conflicting ideas are juxta posed in this response, likely making it difficult for her to use her ideas consistently in unfamiliar scenarios.

Among the students who, overall, provided more incorrect than correct responses, Olivia was particularly interesting because her ideas appeared to shift from the beginning to the end of Section One of the activity. She begins by stating incorrectly that “when bonds are broken, energy is released” and that “when bonds build something up, energy is needed.” Olivia also explicitly writes: “The breaking of the oxygen-phosphate bond would not require energy.” However, after completing the question involving the reaction coordinate diagram, she appears to reconsider, writing that she now thinks “Jaime was right in saying an input of energy is required to break the bond, but then much more energy is released.”

### How ATP Hydrolysis Powers a Molecular Motor

In the second portion of the activity, we attempted to provide students an opportunity to connect their ideas about energy and bonding in the context of a biological phenomenon. The scaffolded series of questions began with a prompt about how many ATP molecules would be needed to package the particular genome and ended with the questions in which we had the most interest: “What happens to the orange protein subunit when ATP is hydrolyzed?” (Q6d) and “Why are the physical interactions between ATP and the motor so important?” (Q6e). A hint to consider the shape of the protein subunit was added to Q6e in the 2019 administration. We coded student responses to this question within three independent categories considering (1) what students discussed as initiating this process, (2) whether and how they recognized the movement of the protein subunits as an important component of the mechanism, and (3) the overall effect on the molecular motor. In each category, we observed a range of student responses.

First, we examined what students said or implied was the source of energy for this molecular motor (Figure 3A). Given that the students had just completed the series of questions about overall energy release during ATP hydrolysis, we expected they would readily identify these physical interactions as important because energy is needed to drive the molecular motor and because the release of inorganic phosphate ($P_i$) demonstrating hydrolysis) is clearly shown in the supporting video. The majority of students simply restated that the interactions were important without bringing in ideas about energy, or they attributed the function of the motor simply to ATP itself without being more descriptive. Only a few students described hydrolysis as providing energy to the system, such as Nathan, who wrote: “When ATP is hydrolyzed into ADP + $P_i$, it releases energy for the motor to use.”

We then considered whether and how students had discussed the mechanistic role of the protein subunits (Figure 3B). The video shows coordinated movement of the relevant subunits and shape change as ATP binds and is subsequently hydrolyzed. We expected students to describe the change in physical shape of the protein subunit as an important mechanistic component of the overall process, especially with the addition of the hint in Q6e to “consider the shape of the orange protein subunit” in the 2019 administration. Some students did discuss movement and shape change (41% in 2018 and 29% in 2019), such as Ben, who wrote that “the small, protracted part of the protein moves down, also moving down the DNA strand.” However, the plurality of student responses in both years were coded as “protein only,” with representative responses like that of Carey (“The protein binds to the ATP”), who recognized the importance of the protein but without an explicit acknowledgment that the protein physically moves and indeed changes shape to ratchet the DNA into the bacteriophage capsid.

Last, we coded student responses for the ways in which they described the effect of the motor (Figure 3C). We preferred responses that specifically recognized DNA being packaged in the phage, such as that from Carter, who wrote that “the hydrolysis of ATP is used to push the DNA genome double helix into the phage capsid,” over those that included DNA moving more generally. Many students referred simply to a general effect of the motor being “powered” or “using energy,” such as Juanita, who responded that the physical interactions between ATP and the motor are important “because the shape allows for the motor to fit and the process to carry out.” This category also had the largest proportion of students coded as “other” or “non-normative,” indicating that the prompt needs revision to elicit better evidence of what students really know about the effect of the packaging mechanism. Future iterations of the activity should provide better scaffolds toward this end.

### Table 2. The range of responses among students coded as “partial.”

| Student responses                              | N (%) |
|-----------------------------------------------|-------|
| Gave more correct than incorrect responses    | 39 (45) |
| Gave an equal number of correct and incorrect responses | 14 (16) |
| Gave more incorrect than correct responses    | 33 (38) |
| Total students coded as “partial”             | 86 (100) |
Comparing Responses

To investigate the extent to which students connected ideas across biology and chemistry as proposed, we compared the results for the “bond breaking and forming” category (based on the first section) and the “initiation” category (based on the second section) (Figure 4). Here, we grouped students by their “bond breaking and forming” code so as to generate two comparable groups: one that had responded correctly, though perhaps incompletely, to Section One of the activity and one that had provided one or more incorrect statements. Even though the majority of students had access to at least one correct idea about the role of energy in bond breaking and forming, most students did not clearly relay that the energy needed to power the motor comes from the interactions between ATP and the motor during hydrolysis; there was no significant difference in the initiation category codes between the two groups ($Mann-Whitney U = 4622, p = 0.73$).

Rather, regardless of their response to the “bond breaking and forming” category, most students relied on the problematic shorthand of claiming that ATP stores, provides, or even is the energy needed to power the motor, including Jerry, who responded that “ATP molecules are what is giving the motor energy.” Similarly, Joey, one of the interviewed students, had not realized that the two sections of the activity were related until the interview itself, when he said the connections between the two sections “made a lot more sense.” While some students who provided (optional) feedback relayed that “it was great to think about ATP in more depth” and they “liked how it made you connect concepts,” others conveyed that they were confused and wished they had “understood the ATP and bacteriophage introduction a little bit more in class.”

Together, these data support prior observations that while students can generally describe the role of energy in a simple, isolated system, applying that knowledge to a closely related phenomenon remains challenging (Cooper & Klymkowsky, 2013) and must be carefully scaffolded (Kararo et al., 2019; Crandell et al., 2020). Prior studies have shown that students similarly have difficulty in making spontaneous connections involving energy between disciplines (Nagel & Lindsey, 2015), and connections to biology may be particularly challenging to support given that biological phenomena are often highly contextualized (Opitz et al., 2019), as is the case here. Similarly to Chabalengula et al. (2011), while many students were able to define and explain the role of energy in bond breaking

**Figure 3.** Distribution of student responses about the (A) initiation, (B) mechanism, and (C) effect of ATP hydrolysis powering a molecular motor.

**Figure 4.** Comparison of percent responses in the “initiation” category by student groups based on responses to the “bond breaking and forming” category (group 1 = correct or incomplete correct; group 2 = partial, incomplete incorrect, or incorrect).
and forming during hydrolysis, they were not readily able to connect this idea conceptually to the physical interactions relevant to this specific biological process.

○ Conclusion & Implications

Energy is recognized as one of the most difficult ideas across undergraduate science courses, and much prior effort has been focused on describing the ways in which students do and, perhaps more often, do not appropriately connect ideas about the energetics of covalent bond breaking and forming with ATP and its role in a biological system (Ozmen, 2004; Dreyfus et al., 2014; Kohn et al., 2018). Some progress has been made with respect to developing interdisciplinary learning progressions that address challenging ideas like energy (Cooper & Klymkowsky, 2013). Still, many introductory courses remain disconnected from one another, leaving students to make such connections themselves. While we find students having similar difficulties here, we contend that the key contribution of this work is the activity itself because it provides a formative scaffold and scale to unpack a range of student understanding that can be addressed with additional instruction, as needed. That is, even if students have difficulty applying their understanding about energy to this specific scenario, the activity provides instructors an opportunity to address such difficulties through feedback from the instructor or perhaps from fellow students in a recitation or peer-review process. In conjunction with the use of similar activities (Roche Allred et al., 2021), students can be provided more opportunities to think about how ideas are related across courses.

This activity was designed to solicit student understanding about how concepts in one discipline relate to those in another (Gouvea et al., 2013), but the activity could be modified to potentially better support students in building such connected understanding. Any curriculum material needs to fit the local context — indeed, we sought guidance from our local instructional community as co-designers (Severance et al., 2016). Thus, rather than suggesting strict fidelity of implementation (Furtak, 2017) in replicating the activity as described here, we close by offering suggestions for modifications that might potentially better support students in building connected understanding between chemistry and biology.

First, students may benefit from being prompted more explicitly to think about physical distances between the molecules and structures involved — for example, by adding the question “Where are the water molecules that would hydrolyze the ATP that facilitates the DNA packaging?” Second, using the theory of negative knowledge, purposely incorporating an incorrect element in a representation has been related to gains in conceptual knowledge (Wernecke et al., 2018). Here, modifying the image of ATP and the motor to show ATP at a distance might be fruitful for prompting students to see the importance of proximity between the structures involved. Third, given the importance of providing opportunities for students to express and refine their own ideas (Ryoo et al., 2018), instructors might add additional open-ended questions, especially for complicated and foundational ideas like how energy facilitates biological processes.

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References

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

Arjoun, J.A., Xu, X. & Lewis, J.E. (2013). Understanding the state of the art for measurement in chemistry education research: examining the psychometric evidence. Journal of Chemical Education, 90, 536–545.

Bain, K., Bender, L., Bergeron, P., Caballero, M.D., Carmel, J.H., Duffy, E.M., et al. (2020). Characterizing college science instruction: the Three-Dimensional Learning Observation Protocol. PLoS ONE, 15, e0239640.

Bain, K. & Towns, M.H. (2018). Investigation of undergraduate and graduate chemistry students’ understanding of thermodynamic driving forces in chemical reactions and dissolution. Journal of Chemical Education, 95, 512–520.

Bretz, S.L. (2019). Designing assessment tools to measure students’ conceptual knowledge of chemistry. In D.M. Bunce & R.S. Cole (Eds.), Tools of Chemistry Education Research (pp. 155–168). Washington, DC: American Chemical Society.

Carnegie Classifications of Institutions of Higher Education (n.d.). http://carnegieclassifications.iu.edu/ (retrieved June 21, 2020).

Chabalenga, V.M., Sanders, M. & Mumba, F. (2012). Diagnosing students’ understanding of energy and its related concepts in biological context. International Journal of Science and Mathematics Education, 10, 291–266.

Chen, X. (2013). STEM attrition: college students’ paths into and out of STEM fields (NCES 2014–001). National Center for Education Statistics, Institute of Education Sciences, U.S. Department of Education.

Cooper, M.M., Caballero, M.D., Ebert-May, D., Fata-Hartley, C.L., Jardeleza, S.E., Krajcik, J.S., et al. (2015). Challenge faculty to transform STEM learning. Science, 350, 281–282.

Cooper, M.M. & Klymkowsky, M.W. (2013). The trouble with chemical energy: why understanding bond energies requires an interdisciplinary systems approach. CBE–Life Sciences Education, 12, 306–312.

Cooper, M.M., Underwood, S.M. & Hillez, C.Z. (2012). Development and validation of the Implicit Information from Lewis Structures Instrument (IILSI): do students connect structures with properties? Chemistry Education Research and Practice, 13, 195–200.

Crandell, O.M., Lockhart, M.A. & Cooper, M.M. (2020). Arrows on the page are not a good gauge: evidence for the importance of causal mechanistic explanations about nucleophilic substitution in organic chemistry. Journal of Chemical Education, 97, 313–327.

Dreyfus, B.W., Sawtelle, V., Turpen, C., Gouvea, J. & Redish, E.F. (2014). Students’ reasoning about “high-energy bonds” and ATP: a vision of interdisciplinary education. Physical Review Special Topics–Physics Education Research, 10, 010115.

Ertmer, P.A. & Newby, T.J. (1993). Behaviorism, cognitivism, constructivism: comparing critical features from an instructional design perspective. Performance Improvement Quarterly, 6(4), 50–72.

Furtak, E.M. (2017). Confronting dilemmas posed by three dimensional classroom assessment: introduction to a virtual issue of Science Education. Science Education, 101, 854–867.
Gouvea, J.S., Sawtelle, V., Geller, B.D. & Turpen, C. (2013). A framework for analyzing interdisciplinary tasks: implications for student learning and curricular design. CBE–Life Sciences Education, 12, 187–205.

Harris, C.J., Krajick, J.S., Pellegrino, J.W. & DeBarger, A.H. (2019). Designing knowledge-in-use assessments to promote deeper learning. Educational Measurement: Issues and Practice, 38, 53–67.

Haudek, K.C., Prevost, L.B., Moscarella, R.A., Merrill, J. & Urban-Lurain, M. (2012). What are they thinking? Automated analysis of student writing about acid–base chemistry in introductory biology. CBE–Life Sciences Education, 11, 283–293.

Kararo, A.T., Colvin, R.A., Cooper, M.M. & Underwood, S.M. (2019). Predictions and constructing explanations: an investigation into introductory chemistry students’ understanding of structure–property relationships. Chemistry Education Research and Practice, 20, 316–328.

Kohn, K.P., Underwood, S.M. & Cooper, M.M. (2018). Energy connections and misconceptions across chemistry and biology. CBE–Life Sciences Education, 17, ar3.

Laverty, J.T., Underwood, S.M., Matz, R.L., Posey, L.A., Carmel, J.H., Caballero, M.D., et al. (2016). Characterizing college science assessments: the Three-Dimensional Learning Assessment Protocol. PLoS ONE, 11, e0162333.

Liu, S., Chistol, G., Hetherington, C.L., Tafoya, S., Aathavan, K., Schnitzbauer, J., et al. (2014). A viral packaging motor varies its DNA rotation and step size to preserve subunit coordination as the capsid fills. Cell, 157(3), 702–713.

Matz, R.L., Fata-Hartley, C.L., Posey, L.A., Laverty, J.T., Underwood, S.M., Carmel, J.H., et al. (2018). Evaluating the extent of a large-scale transformation in gateway science courses. Science Advances, 4, eaau0554.

Matz, R.L., Underwood, S.M. & Parent, K.N. (2019). A three-dimensional approach to connecting biology & chemistry. Scientia, January 30.

Mil, M.H.W. van, Postma, P.A., Boerwinkel, D.J., Klaassen, K. & Waarao, A.J. (2016). Molecular mechanistic reasoning: toward bridging the gap between the molecular and cellular levels in life science education. Science Education, 100, 517–585.

Momsen, J.L., Long, T.M., Wyse, S.A. & Ebert-May, D. (2010). Just the facts? Introductory undergraduate biology courses focus on low-level cognitive skills. CBE–Life Sciences Education, 9, 435–440.

Nagel, M.L. & Lindsey, B.A. (2015). Student use of energy concepts from physics in chemistry courses. Chemistry Education Research and Practice, 16, 67–81.

National Research Council (2012). A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. Washington, DC: National Academies Press.

National Research Council (2013). Next Generation Science Standards: For States, by States. Washington, DC: National Academies Press.

Opitz, S.T., Neumann, K., Bernholt, S. & Harms, U. (2019). Students’ energy understanding across biology, chemistry, and physics contexts. Research in Science Education, 49, 521–541.

Özmen, H. (2004). Some student misconceptions in chemistry: a literature review of chemical bonding. Journal of Science Education and Technology, 13, 147–159.

Penuel, W.R., Turner, M.L., Jacobs, J.K., Horne, K.V. & Sumner, T. (2019). Developing tasks to assess phenomenon-based science learning: challenges and lessons learned from building proximal transfer tasks. Science Education, 103, 1367–1395.

Roche Allred, Z.D., Farias, A.J., Kararo, A.T., Parent, K.N., Matz, R.L. & Underwood, S.M. (2021). Students’ use of chemistry core ideas to explain the structure and stability of DNA. Biochemistry and Molecular Biology Education, 49, 55–68.

Ryan, G.W. & Bernard, H.R. (2003). Techniques to identify themes. Field Methods, 15, 85–109.

Ryyo, K., Toutkoushian, E. & Bedell, K. (2018). Exploring different types of assessment items to measure linguistically diverse students’ understanding of energy and matter in chemistry. Chemistry Education Research and Practice, 19, 149–166.

Saville, D. (2011). Ø29 phage molecular motor DNA packaging mechanism – 3D version [video]. YouTube, September 23. https://www.youtube.com/watch?v=H0xDrDaWcdk.

Sawtelle, V. & Turpen, C. (2016). Leveraging a relationship with biology to expand a relationship with physics. Physical Review Physics Education Research, 12, 010136.

Severance, S., Penuel, W.R., Sumner, T. & Leary, H. (2016). Organizing for teacher agency in curricular co-design. Journal of the Learning Sciences, 25, 531–569.

Shepard, L.A. (2000). The role of assessment in a learning culture. Educational Researcher, 29(7), 9–14.

Sibanda, D. & Hobden, P. (2015). Planning a teaching sequence for the teaching of chemical bonding. African Journal of Research in Mathematics, Science and Technology Education, 19, 23–33.

Underwood, S.M., Posey, L.A., Herrington, D.G., Carmel, J.H. & Cooper, M.M. (2018). Adapting assessment tasks to support three-dimensional learning. Journal of Chemical Education, 95, 207–217.

Wernecke, U., Schütte, K., Schwanewedel, J. & Harms, U. (2018). Enhancing conceptual knowledge of energy in biology with incorrect representations. CBE–Life Sciences Education, 17, ar5.

Wongpakaran, N., Wongpakaran, T., Wedding, D. & Gwet, K.L. (2013). A comparison of Cohen’s kappa and Gwet’s AC1 when calculating inter-rater reliability coefficients: a study conducted with personality disorder samples. BMC Medical Research Methodology, 13, article 61.

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