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ARTICLE

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Students' use of chemistry core ideas to explain the structure and stability of DNA

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Abstract
Students tend to think of their science courses as isolated and unrelated to each other, making it difficult for them to see connections across disciplines. In addition, many existing science assessments target rote memorization and algorithmic problem-solving skills. Here, we describe the development, implementation, and evaluation of an activity aimed to help students integrate knowledge across introductory chemistry and biology courses. The activity design and evaluation of students' responses were guided by the *Framework for K-12 Science Education* as the understanding of core ideas and crosscutting concepts and the development of scientific practices are essential for students at all levels. In this activity, students are asked to use their understanding of noncovalent interactions to explain (a) why the boiling point differs for two pure substances (chemistry phenomenon) and (b) why temperature and base pair composition affects the stability of DNA (biological phenomenon). The activity was implemented at two different institutions ($N = 441$) in both introductory chemistry and biology courses. Students' overall performance suggests that they can provide sophisticated responses that incorporate their understanding of noncovalent interactions and energy to explain the chemistry phenomenon, but have difficulties integrating the same knowledge to explain the biological phenomenon. Our findings reinforce the notion that students should be provided with opportunities in the classroom to purposefully practice and support the use and integration of knowledge from multiple disciplines. Students' evaluations of the activity indicated that they found it to be interesting and helpful for making connections across disciplines.

KEYWORDS
cross-disciplinary activity, DNA denaturation, intermolecular forces

1 | INTRODUCTION

Addressing the large-scale challenges our world faces, such as human-induced climate change, the availability of clean water, and global health issues will take ingenuity and teams of individuals that possess a deep understanding of multiple disciplines.[1–3] To meet these current and future demands of our world, students should acquire strong foundations in science, technology, engineering, and mathematics disciplines.[2] All students should be provided with opportunities to develop and integrate knowledge of multiple disciplines for their future careers and everyday lives. As instructors in introductory science courses at the university level, we have the opportunity to assist students in connecting ideas across disciplines to help prepare them for their future careers.[2,3]

The need for materials that help students make connections both between science courses and with other related disciplines has been recognized by students and instructors alike.[4–8] As a way to provide these opportunities, both researchers and practitioners have set out to develop assessments,[9,10] lessons,[6,11,12] tutorials,[13] and even whole courses[14–16] meant to help students integrate multiple disciplines such as chemistry, biology, physics, and mathematics.[17] Implementations of some of these materials have suggested that students who are exposed to multidisciplinary experiences exhibit a positive attitude and develop a greater interest in science than students who are not.[9,13]

Furthermore, in recent years, considerable efforts have been made by researchers, practitioners, and leaders in science education toward the development of assessment tasks that reflect the vision proposed by the National Research Council's *Framework for K-12 Science Education* (the Framework).[18–23] According to the Framework[18] students should be able to integrate disciplinary core ideas (with predictive and explanatory power), scientific practices (the ways that scientists use and apply knowledge), and crosscutting concepts (productive lenses, tools, bridges, and rules for problems[24,25]). The integration of these three strands is referred to as "three-dimensional learning" or 3DL. While the Framework is intended for the K-12 level, this approach is also relevant to college-level students.[26,27]

The lack of connections across disciplines can leave students with the impression that science is a collection of well-defined and isolated facts.[4,28] The phrase "a mile wide and an inch deep" has been used to characterize science and math curricula in the United States.[29] Alternatively, 3DL is meant to move students away from this more traditional approach that tends to overwhelm students with large amounts of content, leading them to rely on factual knowledge. Instead, 3DL encourages the development of deep and usable knowledge that students could apply later in new contexts.[3,30–33] If students are taught using the 3DL Framework, then the assessments should also incorporate all three dimensions, moving away from assessments that focus on low-level cognitive skills and foster algorithmic thinking and rote memorization.[3,20,22,26,32–34]

Aware of the need to provide students with opportunities to practice using their knowledge purposefully across disciplines, our work focuses on the development, implementation, and evaluation of knowledge-in-use activities that integrate biology and chemistry. Our activities build from previous work on the development of assessments designed to promote deeper learning by engaging students in new situations where they use and apply their knowledge to solve problems or make sense of phenomena.[20,22,34] These activities are intended to integrate chemistry core ideas, scientific practices, and crosscutting concepts across disciplines. In addition to helping students integrate their knowledge of chemistry and biology within these activities, the 3DL Framework was used to design questions that would guide students to think deeply about the topic. The activity presented here, and similar activities developed through the larger project, contribute to the currently limited number of assessments available that integrate core ideas, scientific practices, and crosscutting concepts.[19–21,34]

The integration of chemistry and biology was of special interest for this work because discoveries in biology increasingly occur at the intersections of established disciplines[1,35] and, as highlighted by the American Association for the Advancement of Science report *Vision and Change in Undergraduate Biology Education*, biological phenomena result from chemical pathways that are governed by the laws of thermodynamics.[7] Therefore, as part of a larger project,[36] we are developing activities that ask students to use chemistry core ideas to explain biological phenomena. We draw on the prior work of chemistry faculty from one of our institutions who, with the aim of defining what students should know and do with their knowledge, identified four core ideas: (a) electrostatic and bonding interactions; (b) change and stability in chemical systems; (c) atomic/molecular structure and properties, and (d) energy—at the macroscopic, molecular, and quantum levels.[26,37] Here, we present an activity that asks students to use their understanding of noncovalent interactions (chemistry core idea—*electrostatic and bonding interactions*) to explain the structure and stability of DNA (biological phenomena).

Noncovalent (electrostatic) interactions were chosen as a focus for three particular reasons. First, electrostatic and bonding interactions have been identified through multiple initiatives as a core idea in chemistry.[26,38,39] Second, previous research has highlighted students' difficulties with noncovalent interactions, particularly hydrogen bonding.[40–43] Common alternative ideas include thinking that *all* hydrogen atoms are capable of hydrogen bonding and that hydrogen bonds are the covalent bond between hydrogen and another atom within a molecule.[40,43] Third, electrostatic forces play a crucial role in the structure and stability of biological systems, and the interactions between and within biological systems, which has led researchers to identify electrostatic interactions as a threshold concept in biochemistry,[44] meaning that if students do not possess a deep understanding of noncovalent interactions, they will have difficulties gaining a conceptual understanding of ideas taught in more advanced courses like biochemistry. To develop the activity presented herein, we relied on previous research of student understanding of noncovalent interactions and the structure and stability of DNA[45,46] and noncovalent interactions within proteins.[47–49]

The learning goals for this activity are as follows:

1. Integrate multiple chemistry core ideas to explain a chemistry phenomenon.
2. Apply chemistry core ideas to explain a biological phenomenon.

2 | METHOD

In the following subsections, we will describe how our team, composed of three professors, two postdoctoral researchers, and one undergraduate researcher, developed, implemented, and evaluated an activity aimed to help students integrate knowledge across introductory chemistry and biology courses. More details on the roles of each team member are provided in the Supporting Information S.1. The activity presented in here will be referred to as the DNA activity.

2.1 | Selecting the phenomenon of interest

This activity is part of a larger project that involves the development of multiple knowledge-in-use activities guided by the 3DL Framework.[36] Given the large number of potential connections between general chemistry and introductory cell and molecular biology, we first identified which connections between chemistry and biology instructors most valued. These areas of interest were identified by surveying the instructors ($n = 11$) at one of our institutions for convenience. The results obtained from the survey helped us prioritize the development of activities (including this DNA activity) with the connections that were of most relevance and interest to local practitioners.

2.2 | Activity design

The DNA activity was developed using a simplified version of evidence-centered design.[50] Using this method, we determined the overall goal of the activity, which articulates what students should know and be able to do: students can apply their understanding of noncovalent interactions and the structure of DNA to explain the relationship between hydrogen bonding, temperature, and the stability of DNA. We also determined what evidence would help us identify whether students were making connections between the chemistry and biology concepts (see Section 3). The overall design of the activity included questions across three main sections: (a) a chemistry phenomenon, (b) a connection between chemistry and biology, and (c) a biological phenomenon (outlined in Figure 1) with each section incorporating the three dimensions described in the Framework.[18] The *Three-Dimensional Learning* Assessment *Protocol* (3D-LAP)[26] was used to verify that the activity had the potential to elicit student ideas regarding each of the dimensions (see Table S.2 in Supporting Information).

The chemistry phenomenon section of the activity (Table 1, Questions 2 and 3) included the common task used in general chemistry to explain the boiling point differences between substances. Students were presented with Lewis structures and the boiling points for two sets of substances and asked to use their understanding of noncovalent interactions (for this activity we mainly focused on hydrogen bonding) to construct an explanation about the difference in boiling points. Student responses to these questions helped us better understand their chemistry knowledge (with respect to *electrostatic*

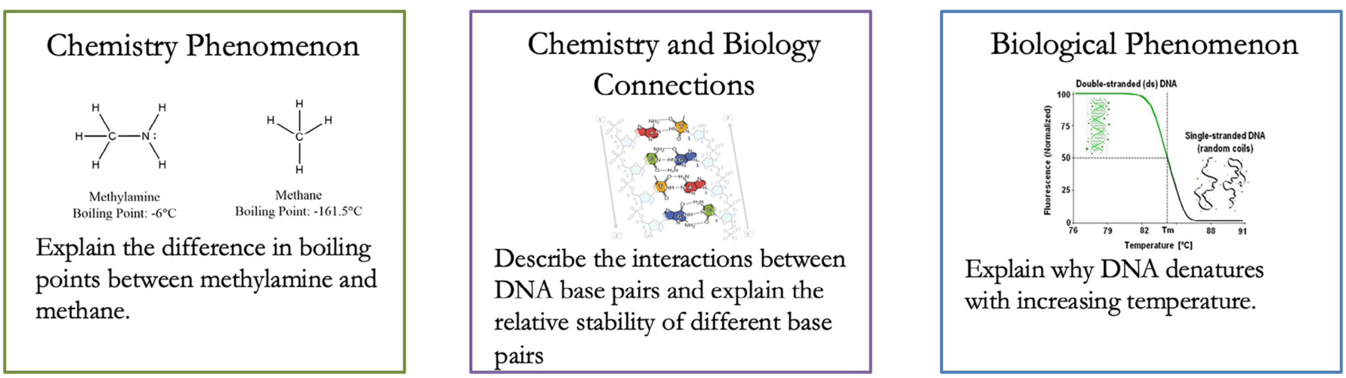


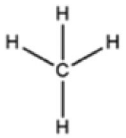
FIGURE 1 The three main sections of the DNA activity [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 DNA activity administered to students in Environments II and III in Figure 2. [Color table can be viewed at wileyonlinelibrary.com]

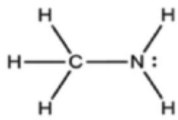
Application of intermolecular forces in a biological system

1. In 1–2 sentences, what do you know about intermolecular forces?

2. Consider a container of pure liquid methane and a separate container of pure liquid methylamine:



Methane
Boiling Point: -161.5°C



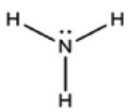
Methylamine
Boiling Point: -6°C

(a) List *all* the types of intermolecular forces that would be present in the liquid form of each of the pure substances.

Liquid methane:
Liquid methylamine:

(b) Use your understanding of intermolecular forces and the boiling points (data) above to explain why methylamine has a higher boiling point than methane.

3. Now consider a container of pure liquid ammonia and a separate container of pure liquid water:



Ammonia
Boiling Point: -33.3°C

Water
Boiling Point: 100°C

(a) List *all* the types of intermolecular forces that would be present in the liquid form of each of the pure substances.

Liquid ammonia:
Liquid water:

(b) Use your understanding of intermolecular forces and the boiling points (data) above to explain why water has a higher boiling point than ammonia

4. Intermolecular forces are also important for the composition of DNA. The following figure shows how two DNA strands interact in a double-stranded helix. The figure shows the bases: thymine (T colored in orange), adenine (A—red), guanine (G—blue) and cytosine (C—green), which are essential parts of DNA. Please note that the DNA bases can only pair up as A with T and C with G as shown to the right.

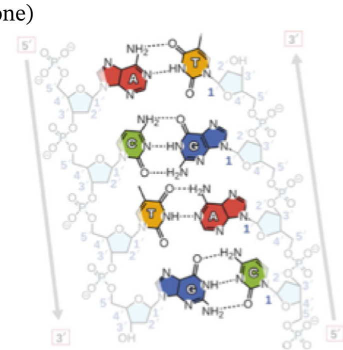
(a) List the *strongest* type of intermolecular force that can form between a thymine base on one strand of DNA and an adenine base on the other strand.

(b) Which base pair is more stable as temperature increases? (circle one)

i. T-A is more stable
ii. G-C is more stable
iii. They have the same stability
iv. Not enough information to predict

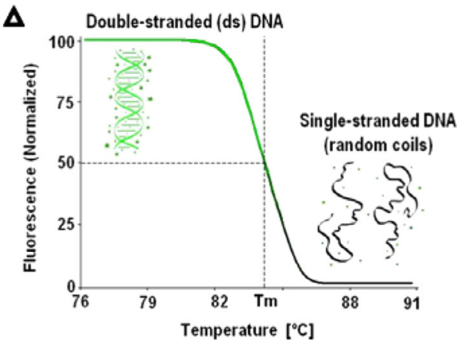
(c) Explain your reasoning for your selection.

*



5. Consider the following graph, showing the denaturation of DNA (when the two strands of DNA separate from one another). Use your understanding of intermolecular forces to explain what is happening that causes the DNA to denature.

△



6. Samples of DNA with different base pair sequencing ratios will have different temperatures at which the DNA will denature. Consider two DNA samples: Sample #1 has 40% A-T content and Sample #2 has 65% A-T content.

(a) The figure above shows the temperature of melting (T_m) for Sample #1. What would the relative T_m be for Sample #2?

i. Sample #2 would have a *higher* T_m than Sample #1
ii. Sample #2 would have a *lower* T_m than Sample #1
iii. Sample #2 would have the *same* T_m as Sample #1
iv. Not enough information to predict

(b) Use your understanding of intermolecular forces and the base pair sequencing of the two DNA samples to explain your reasoning.

TABLE 1 (Continued)

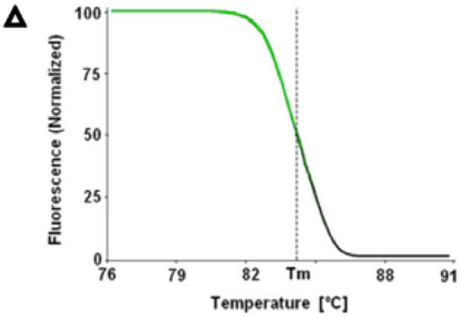
Application of intermolecular forces in a biological system
7. The following figure again shows the denaturation of DNA for Sample #1:

(a) Using a dotted line, draw your prediction for the T_m of Sample #2 on the graph.
(b) Explain your reasoning for the graph you drew in Part a.

*Image modified from Parker et al., Microbiology (2016), https://openstax.org/books/microbiology/pages/10-2-structure-and-function-of-dna (accessed December 09, 2019).

ΔImage retrieved and modified from: Wittwer Lab, High-Resolution Melting 2019, https://www.dna.utah.edu/Hi-Res/TOP_Hi-ResMelting.html (accessed October 12, 2019).

and bonding interactions and *atomic/molecular structure and properties*) prior to introducing the biological phenomenon.

In the chemistry and biology connection section (Table 1, Question 4), students were asked to make connections between the core ideas elicited in the chemistry phenomenon section (Table 1, Questions 2 and 3) and a macromolecule of DNA. Specifically, students were asked to identify the type of noncovalent interactions present between base pairs in double-stranded DNA and use this knowledge to identify and construct an explanation about the base pair stability as temperature increases.

As part of the biological phenomenon section (Table 1, Questions 5–7), students were shown a graph depicting the change in fluorescence of DNA as temperature increases (i.e., a DNA melting curve). They were asked to analyze and interpret the melting curve to explain what is happening that causes DNA to denature. Students were also asked to think about how melting temperature would be different for two samples of DNA with varying base pair compositions. Responses to these questions allowed us to examine if students could use and apply their understanding of noncovalent interactions, molecular structure–property relationships, and the structure of DNA to explain the relationship between hydrogen bonding, temperature, and the stability of DNA.

The discussion in this study will focus on student responses to one of the chemistry phenomenon questions (Table 1, Question 2) and one of the biological phenomenon questions (Table 1, Question 5). While two versions of the DNA activity were administered, both shared three main sections: (a) chemistry phenomenon, (b) connection between chemistry and biology, and (c) biological phenomenon with comparable questions (Figure 1). The complete activity can be found in Table 1.

2.3 | Participants

The activity was designed for students at the introductory levels of chemistry and biology. Two comparable versions of the activity were given to four groups of students at two research-intensive institutions to develop an initial understanding of how students would interact with this activity. Students from University 1 (Univ 1) were from a large Midwestern public institution with predominantly Caucasian students. Participants from University 2 (Univ 2) were from a large Southeastern public institution serving predominantly Hispanic students. This project was approved as exempt research by the Institutional Review Board at each university since the nature of the study presented minimal risk to the participants.

2.4 | Implementation conditions

The activity was implemented in three different instructional environments (Figure 2). In the first implementation

(Environment I), students from both Univ 1 ($n = 200$) and Univ 2 ($n = 51$) were given the initial version of the activity during Spring 2018 at the end of their second semester of general chemistry (students from these environments will be referred to as I—Univ 1 and I—Univ 2, respectively). The activity was administered as a homework assignment via an online assessment system called *beSocratic*, which functions like a set of PowerPoint slides and allows students to submit both drawings and written responses.[51] Each question was presented on a different slide. Students were informed that they could not move backward through the activity and that they should try their best to answer all the questions without consulting outside resources (i.e., classmates, internet, notes) because we were interested in their baseline understanding of different chemistry and biology topics. This first version of the activity presented students with the same biological phenomenon twice, at the beginning and end of the activity (Figure 2). The purpose of this approach was to gather data on students' initial viewpoints about DNA denaturation and whether students' ideas changed after answering the chemistry core idea questions. In addition, these students were asked about their familiarity and confidence with the concepts of DNA structure, DNA melting curves, noncovalent interactions, and hydrogen bonding using Likert scale questions.

For the subsequent administrations, the activity was modified due to students' unfamiliarity with the denaturation of DNA when first introduced to the melting curve (see plots in Supporting Information S.3) and their limited use of chemistry core ideas to explain the biological phenomenon. The activity was modified to present students with the biological phenomenon questions only after the chemistry phenomenon questions. This new version was administered to students at Environment II—Univ 1 (referred to as II—Univ 1) and at Environment III—Univ 2 (referred to as III—Univ 2) as a worksheet rather than with *beSocratic* (Figure 2).

Students ($n = 92$) from II—Univ 1 were given the activity during Fall 2018 at the end of their first semester of biology. This modified activity was implemented as an extra credit homework assignment. The majority of these students were concurrently enrolled in a general chemistry (I or II) course (14%) or had taken a general chemistry (I or II) course at least one or two semesters (Summer 2018, Spring 2018) before completing the activity (44%). Students from Environment III were in general chemistry I at Univ 2 during Fall 2018. These students ($n = 98$) were given the activity as an in-class assignment during instruction regarding noncovalent interactions. Regardless of the implementation, after completing the activity all students were given the option to provide any feedback or thoughts they had about the activity.

It is important to note that both universities implement the general chemistry curriculum known as *Chemistry, Life, the Universe and Everything*.[52] This curriculum

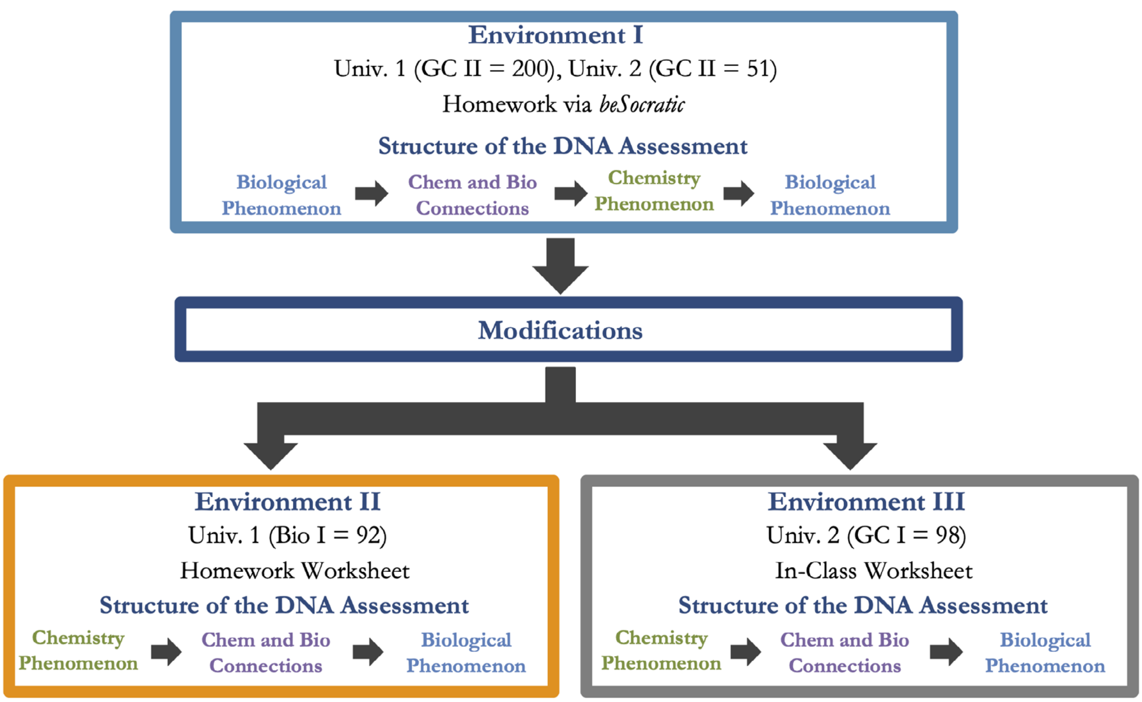


FIGURE 2 Implementation conditions for DNA activity across the two universities [Color figure can be viewed at wileyonlinelibrary.com]

is designed to help students construct a sophisticated and connected understanding of the four core ideas in chemistry.[52] In addition, the overall introductory biology sequence at Univ 1 places significant emphasis on seven core ideas: (a) chemical and the physical basis of life; (b) matter and energy; (c) cellular basis of life; (d) systems; (e) structure and function; (f) information flow, exchange, and storage; and (g) evolution[26] which were inspired by the *Vision and Change* report[7] as well as the Framework.[18] The curricular framing provided by the courses played an essential role in development of the activity and our interpretations of students' responses.

2.5 | Analysis of student responses

The student responses from both versions of the activity were sorted for completion prior to analysis. Students who completed less than half of the activity were removed (1% I—Univ 1, 9% I—Univ 2, 2% II—Univ 1, 30% III—Univ 2) from the data set since the purpose of the activity is to have students incorporate their understanding demonstrated at the beginning of the activity into their explanations at the end of the activity. It should be noted that some students in III—Univ 2 were not able to finish due to class time constraints. All multiple-choice and Likert scale questions from Environment I were exported from *beSocratic* and the multiple-choice questions from Environments II and III were transcribed from the worksheets to Excel. Student responses to the multiple-choice questions were tallied to determine the number of students answering these questions correctly. As for the Likert scale questions, student responses were also tallied to determine their familiarity and confidence with the concepts of DNA structure, DNA melting curves, noncovalent interactions, and hydrogen bonding.

The open-ended questions were analyzed using the coding schemes for each question described below; the complete coding schemes are available in Table 2 and the Supporting Information (Tables S.4–S.6). Since the goal of the activity is to help students use chemistry core ideas to explain a biological phenomenon, prior to developing the coding schemes, we identified the concepts or components that were essential for the construction of well-developed explanations. For example, we expected a complete student response to the biological phenomenon question (Table 1, Question 5) to include students referring to interactions being overcome, temperature, and energy. Given that student responses could include multiple concepts, the codes created were arranged in increasing levels of sophistication (Table 2). Rather than classifying student responses as correct or incorrect, this coding scheme allowed us to detect a range of student ideas.

For the biological phenomenon question (Table 1, Question 5), some students only discussed interactions/bonds being broken, while others took into consideration how an increase in temperature leads to more energy, causing bonds/interactions to break. An additional difficulty associated with hydrogen bonds is the word "bonds" which refers not to covalent bonds but permanent dipoles.[40,41,43] Given that students find the language of hydrogen bonds confusing, we had difficulties distinguishing whether they were referring to a noncovalent interaction or a covalent bond when they used the word "bond". For this reason, we combined student responses that used the terms bonds and interactions as we did not have enough information in their responses to decipher their use of language. Responses that included unrelated concepts from the ones we identified as essential to constructing an explanation or that did not fall into any of the other codes were coded as "Other." The final coding scheme for the biological phenomenon question with definitions and examples of students' responses is shown in Table 2.

The responses to the chemistry phenomenon question (Table 1, Question 2) were coded using the coding scheme published by Kararo and colleagues for students' explanations of boiling point.[53] A copy of this coding scheme with examples from the DNA activity is provided in the Supporting Information (Table S.4). We also developed a coding scheme for the chemistry and biology connection question, which is described in Supporting Information S.5.

2.6 | Validity and reliability

Multiple sources of evidence were gathered to establish the validity and reliability of the data generated by the DNA activity. The activity was developed by our team of disciplinary-based education researchers in biology and chemistry, who helped establish the criteria for the development of items that included and connected both biological and chemical content. In addition, a panel of four external disciplinary experts in biology, chemistry, and biochemistry evaluated the accuracy of the items developed as part of the DNA activity. They provided comments and suggestions that were used to modify the activity prior to its initial implementation.

During the implementation of the activity in Environment I, students were asked to provide feedback or suggestions for the activity as an optional task. This allowed us to gather face-validity evidence that the students were interpreting the items as intended. From the 188 students who provided comments, several discussed their uncertainty in what was meant by DNA composition (base pair composition). Therefore, related questions

TABLE 2 Coding scheme used to evaluate student responses to the biological phenomenon question (Q5)

Code	Definition	Example of students' responses
Non-normative	Student uses scientifically inaccurate or unrelated reasoning	"Those IMFs are being broken, releasing energy." (Student from II—Univ 1)
Bonds/interactions broken	Student states bonds/interactions are broken/ overcome but does not provide any more information	"Intermolecular forces are being overcome causing the double-stranded DNA to denature and become single-stranded DNA." (Student from III—Univ 2)
Temperature added to break bonds/interactions	Student states that increasing temperature causes bonds/interactions to break or be overcome	"As temperature increases the intermolecular forces between molecules are being overcome. The hydrogen bonds between A-T + G-C are overcome, and the strands separate/ denature." (Student from II—Univ 1)
Energy needed to break bonds/interactions	Student states that increasing energy causes bonds/interactions to break or be overcome	"The more energy (heat) that is added the more H-bonds (IMF) will break, eventually resulting in all of them breaking and the DNA strands separate." (Student from I—Univ 2)
Temperature added meaning more energy is added to break bonds/interactions	Student states that increasing temperature leads to more energy which causes bonds/ interactions to break or be overcome	"As the temperature increases the molecules absorb enough energy to be able to break the hydrogen bonds that it has." (Student from I—Univ 1)
Other	Students' response does not fall into any of the codes listed above	"DNA strands separate at high temperatures." (Student from I—Univ 2)

were modified for clarification before implementation in Environments II and III (Figure 2). In this newer version of the activity, students were presented with the percent composition of base pairs for two DNA samples and asked to predict the differences in melting temperatures for the samples and explain their reasoning (Table 1, Questions 6 and 7). After the implementation of the activity in Environments II and III, response process validity interviews were performed with seven chemistry learning assistants from Univ 2 and seven biology students from Univ 1. This allowed us to ensure that students were interpreting the modified questions and the figures as intended. The modifications that were made are further discussed below in the Section 3.4.

Establishing content validity and face validity (response process validity) are common practices in our field and essential in the development of instruments.[54,55] These forms of validity enable us to generate evidence against the threats to the validity of the results obtained from the multiple implementations of the DNA activity. In addition to establishing the validity of activity, we support the reliability of our analysis by calculating the inter-rater reliability with Cohen's kappa (κ), a commonly used coefficient in our field.[56–59] During the analysis process, raters received directions on the coding scheme and how to record their coding. One rater coded a set of student responses for a cohort, a second rater coded a random 20% of the data set from the same cohort, and we obtained κ values ranging from 0.9 to 1.0 depending on the specific question (see Supporting Information S.7 for the Cohen's κ ranges).

3 | RESULTS AND DISCUSSION

3.1 | Learning Goal 1: Integrate multiple chemistry core ideas to explain a chemistry phenomenon

The overall goal of this activity is to provide students with an opportunity to integrate their scientific knowledge from chemistry and biology. Specifically, we wanted students to use their understanding of chemistry core ideas (*electrostatic and bonding interactions* and *atomic/molecular structure and properties*) to explain a biological phenomenon. Thus, in one of the chemistry phenomenon questions (Table 1, Question 2) students were asked to explain why the boiling point of methylamine is higher than methane. Ideally, students would explain that methylamine can interact with other methylamine molecules through hydrogen bonding, dipole–dipole interactions, and London dispersion forces (LDF), while methane can only interact with other methane molecules through LDFs. Therefore, the interactions between methylamine molecules are stronger than the interactions between methane molecules and more energy would be needed to overcome the stronger interactions between the methylamine molecules compared to the methane molecules, resulting in a higher temperature needed to transition from the liquid phase to the gas phase.

Results in Figure 3a indicate that many students from all the environments correctly compared the strength of interactions/bonds that each molecule could form in the liquid phase (strength and strength and energy; 62% I—Univ 1, 55% I—Univ 2, 48% II—Univ 1, 43% III—Univ 2). Of the students that incorporated the concept of strength, some went on to provide more sophisticated responses by incorporating the idea of energy being needed to overcome these stronger attractive electrostatic forces (strength and energy; 39% I—Univ 1, 28% I—Univ 2, 24% II—Univ 1, 14% III—Univ 2). These students provided the most sophisticated reasoning by integrating the concepts of interactions/bonds, strength, and energy correctly in their explanations.

While most students began to incorporate the correct ideas necessary to explain the boiling point trends, some students proved less successful by including scientifically inaccurate (i.e., non-normative) ideas. Consider the following response of a student who wrote that the difference in boiling point for the substances was "due to methylamine having more hydrogens" (I—Univ 1) than methane. Similar students focused on surface features of the Lewis structures rather than discussing the interactions between the molecules, which led them to provide scientifically inaccurate explanations for the differences in boiling points.

We also observed responses from students who did not invoke ideas about noncovalent interactions and energy. These responses were not considered to be scientifically inaccurate explanations, rather they failed to incorporate the components that were essential for the construction of a well-developed explanation about the difference in boiling points for the substances. Therefore, these responses were coded as "Other." More than 25% of students from both I—Univ 2 and II—Univ 1 were coded as "Other" (Figure 3a). Common responses among these students included comparing the polarity of the bonds within each molecule due to differences in electronegativity:

> The methylamine has a higher boiling point because it has more polar bonds than methane. This just means that the elements of methylamine have a greater difference in electronegativity than the difference between elements of methane. (Student from II—Univ 1)

Student responses from III—Univ 2 were unique compared to the other groups in that these students were more focused on how methylamine could form hydrogen bonds while methane molecules could only interact through LDFs (Figure 3a). These results are understandable since these students completed the activity on the same day that formal instruction occurred on noncovalent interactions (i.e., hydrogen bonding and dipole–dipole interactions). That is, these general chemistry students had less exposure to this material than the students in the other chemistry environments presented here, which likely contributed to these students having provided less sophisticated responses. This would suggest that students need to finish the instructional unit on this topic prior to the activity in order to maximize the possibility of using this knowledge to connect to the biological phenomenon.

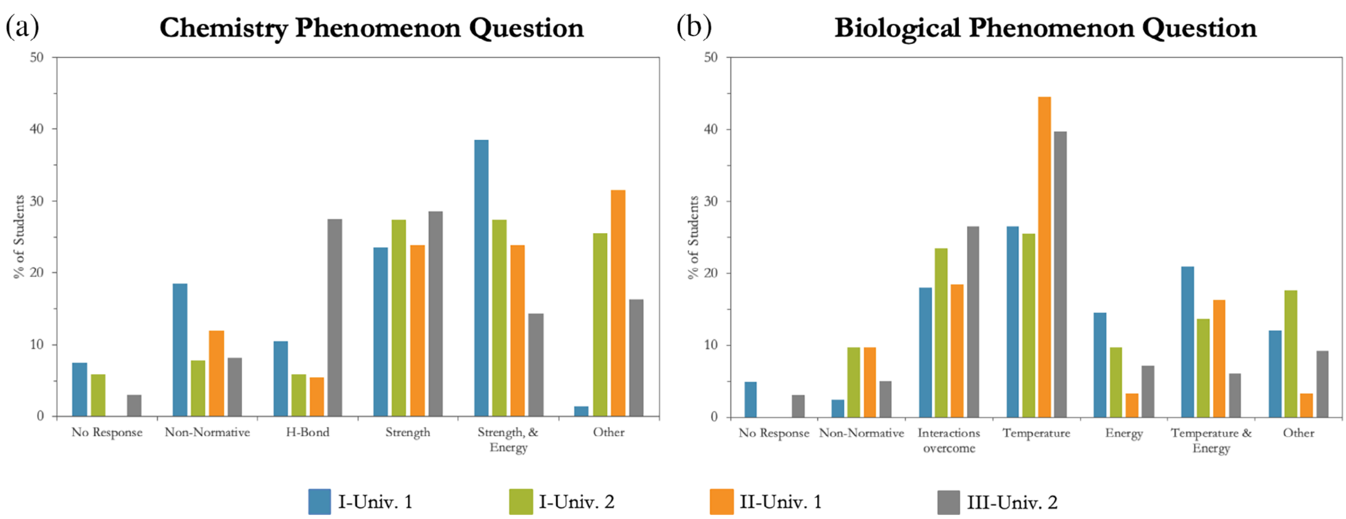


FIGURE 3 **A**. Student responses to the chemistry phenomenon question (Q2), analyzed using the coding scheme in Table S.4. **B**. Student responses to the biological phenomenon question (Q5), analyzed using the coding scheme in Table 2 [Color figure can be viewed at wileyonlinelibrary.com]

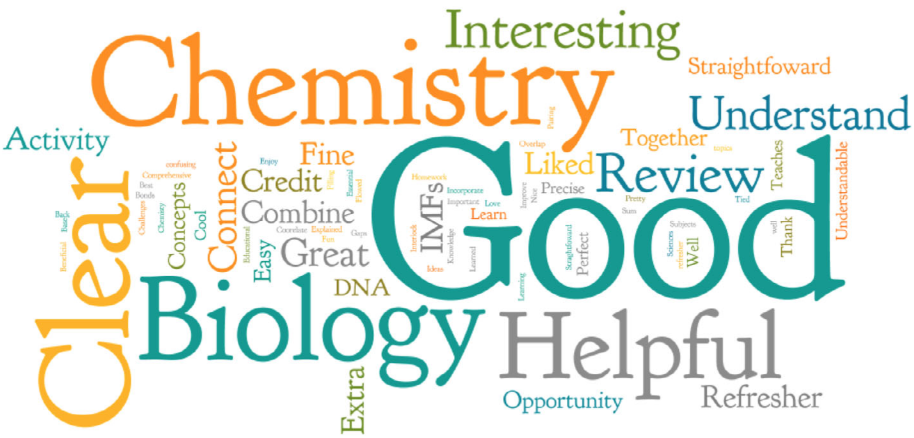


FIGURE 4 Student feedback to the DNA activity represented as a word cloud [Color figure can be viewed at wileyonlinelibrary.com]

3.2 | Learning Goal 2: Apply chemistry core ideas to explain a biological phenomenon

Once we elicited student ideas about multiple chemistry core ideas, they were asked to interpret a DNA melting curve and explain what causes the DNA to denature. Ideally students would explain that as temperature increases, energy is being added to the system, resulting in the hydrogen bonding between the two strands of DNA being disrupted and the two DNA strands separating from one another.

While there were still some students that focused on electrostatic interactions, Figure 3b shows that a large number of students from all environments interpreted the DNA melting curve accurately by stating that an increase in temperature causes the interactions between the DNA strands to be overcome (temperature; 27% I—Univ 1, 26% I—Univ 2, 45% II—Univ 1, 40% III—Univ 2). Similar to the boiling point question, some students provided more sophisticated explanations by incorporating the idea of energy in their responses. These students stated that a higher temperature leads to an increase in energy which disturbs the interactions between the DNA base pairs (temperature and energy; 21% I—Univ 1, 14% I—Univ 2, 16% II—Univ 1, 6% II—Univ 2). Although these students were able to incorporate the concepts of electrostatic interactions, temperature, and energy without being prompted to do so, fewer students were able to integrate multiple concepts for the biological phenomena question than the chemistry question.

Some students provided alternative ("Other") responses (12% I—Univ 1, 18% I—Univ 2, 3% II—Univ 1, 9% III—Univ 2), focusing mostly on describing changes in the structure and shape of DNA as temperature increases without referring to the interactions between the two DNA strands (Figure 3b). For example, one student from I—Univ 2 responded with "The double-stranded DNA at a high temperature makes the DNA single-stranded." It is possible that students who discussed changes in the shape of DNA were only focused on the representation of the DNA strands presented as being annealed at a lower temperature and separated as temperature increases (Figure 1). We also observed some students from both I—Univ 2 (10%) and II—Univ 1 (10%) providing scientifically inaccurate responses (i.e., non-normative). Representative inaccurate explanations included the common and well-documented misconception that energy is released when bonds are broken (Table 2).[60–64]

Based on the results discussed above, it is possible that many of these students did not consider energy as playing a central role in explaining the denaturation of DNA. It is also possible that some students knew that the idea that energy is required to disrupt hydrogen bonds in the chemistry context, but do not have a deep understanding of how temperature, energy, and noncovalent interactions are associated. Previous work has also shown that while students recognize the general importance of energy in science, they believe that energy is more important to understand and think about in the context of chemistry than in biology.[65] Thus, it is possible that students in our sample responded in accordance to what they believe was expected of them in a given course.

Similar results to the DNA denaturation question were obtained when students from Environments II and III were asked to explain the stability of two DNA samples that differ in GC-content (see Supporting Information Table S.6 for the relevant coding scheme and Supporting Information S.8 for Results). When comparing the stability of two DNA samples, more than half of these students only focused on comparing the number and strength of interactions. In addition, about a quarter of these students provided scientifically inaccurate responses. Results from the Likert scale questions on students' familiarity with DNA melting curves also demonstrate their unfamiliarity with the task at hand (see plots in Supporting Information S.3). These results provide further evidence that students have difficulties in integrating knowledge from multiple disciplines and emphasize the importance of providing students with opportunities to use their knowledge in new situations.

3.3 | Student feedback

In addition to having students complete these questions, we asked students to reflect on the activity itself as part of an optional question. Feedback was received from 188 of 441 (43%) students and, overall, the activity was well received; 109 of 188 students provided positive comments. These comments are visualized in Figure 4 as a word cloud, a simple and exploratory qualitative method to visualize data such as students' comments.[66–70] Students stated that they found the activity to be interesting, clear, helpful, and straightforward. Many students also stated that the activity allowed them to review their knowledge of noncovalent interactions and make connections between their biology and chemistry knowledge. For example, one student wrote:

> It's been awhile since I've taken a biology class, and when I last did it wasn't really my favorite, but I really appreciate the opportunity to combine these two fields and use my new chemistry knowledge to connect to ideas I learned years ago! I like to understand things from many different perspectives, and this was very helpful! (Student from III—Univ 2)

Given that some students completed the activity weeks or even months after they were introduced to the concept of noncovalent interactions, it was not surprising to see that some students thought it was necessary to review noncovalent interactions prior to the activity.

> I feel like a quick review over intermolecular forces would help me be able to easily finish the questions on this worksheet that I did not know. (Student from II—Univ 1)

Therefore, we recommend that during future implementations of the activity, it would be beneficial for the instructors to include time for the students to discuss their ideas with each other or for the instructor to lead an in-class discussion. Students who were given the activity as homework discussed how it would have been beneficial for them to discuss whether their explanations and integration between disciplines were appropriate.

3.4 | Modifications

As previously mentioned, during the implementation of the first version via *beSocratic*, multiple students mentioned that they were unsure of what was meant by "DNA composition." We took their comments into consideration and made modifications to clarify related questions before the implementation in Environments II and III (Figure 2). In this newer version of the activity, students were presented with the percent composition of base pairs for two DNA samples and asked to predict the differences in melting temperatures for the samples and explain their reasoning (Table 1, Questions 6–7). Although this modification helped to clarify the composition question, the students found the new set of questions repetitive. For this reason, in the most updated version of the activity (see Supporting Information S.9), further modifications were made to address this concern.

Lastly, given students' difficulties with the ideas of interactions and bonding, during the analysis of student responses, it was difficult to know whether students were referring to bonds *within* a single molecule or interactions *between* molecules. Consequently, when analyzing student responses, both interactions and bonds were coded together. Thus, to be able to gather evidence that the students are referring to interactions between molecules when completing the activity, the most updated version (Supporting Information S.9) asks students to draw noncovalent interactions. Previous studies have provided evidence that the combination of drawing and writing explanations helps students learn and make connections.[43,48,71–74] Students also had multiple difficulties with Question 3 (Table 1) from the chemistry phenomenon section of the activity. As previously mentioned, in order to modify this question, response process validity interviews were performed with seven chemistry learning assistants from Univ 2. The results from these interviews informed the modifications made to the most updated version of this question (Question 3 in Supporting Information S.9), in particular, a hint about the average number of hydrogen bonds each substance can form. Instructor notes with suggestions on how to implement the activity presented in here are provided in Supporting Information S.10.

4 | CONCLUSIONS, IMPLICATIONS, AND LIMITATIONS

The DNA activity provides students with an opportunity to integrate their knowledge from chemistry and biology. Although one of the core ideas in biology is the *chemical and physical basis of life*, students are often not given the opportunity to make connections between these disciplines. In this activity, students are presented with a familiar chemistry phenomenon where they compare the boiling points of two pure substances. Students are then presented with a biological phenomenon where they are asked to explain how changes in temperature and composition affect the stability of DNA using chemistry core ideas. Overall, regarding the chemistry phenomenon students were able to incorporate multiple ideas, including energy without being prompted to do so, but this seemed more challenging to do with the biological phenomenon. However, student responses to the activity provided evidence that when given an experience that affords them the opportunity to use their knowledge from multiple disciplines, they can recognize the connections and integrate their understanding of different disciplines.

While there exists a large number of assessments that can be used to measure student understanding within a discipline, there are fewer assessments that encourage students to integrate their knowledge from multiple disciplines. Our results suggest that while some students are able to incorporate multiple concepts to explain a familiar scenario, many students have difficulties applying the same concepts to explain a new scenario. Thus, if we want our students to develop a deep and integrated understanding of scientific knowledge and apply it to new scenarios, we must give them opportunities to practice integrating their knowledge across disciplines. As an example, after students are formally introduced to and practice the concept of noncovalent interactions, students could be given an activity like the one presented in this article in which they are asked to use their newly learned concepts in a new way (knowledge-in-use). While there is still more work to be done on how to develop tasks that will help students integrate their knowledge from multiple disciplines, the activity presented in this article represents a step in the right direction.

The results presented in this article are limited in that the students completing the activity came from only two institutions. It is important to note that the general chemistry courses at these institutions taken by the majority of students are transformed and emphasize core chemistry ideas. It is unknown whether students from other institutions with different curricula would perform similarly, or if they would require additional prompts to help them make connections between the two disciplines. Future work will explore how students from different chemistry and biology courses histories are impacted by these developed activities.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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