College Students Teaching Chemistry through Outreach: Conceptual Understanding of the Elephant Toothpaste Reaction and Making Liquid Nitrogen Ice Cream

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Supporting Information

ABSTRACT: Informal chemistry education/chemistry outreach is ubiquitous with the chemical enterprise. However, little research has focused on the planning, implementation, or evaluation of these events. Results from a previous study suggest that college students involved with collegiate chapters of the American Chemical Society and Alpha Chi Sigma are heavily involved with chemistry outreach, and their most frequently discussed purpose is to teach chemistry content to their audiences. Given this goal, it is timely to investigate how well these college students, who are acting as teachers in outreach environments, understand the chemistry content embedded in the activities they implement during their events. Presented in this paper are the results of a content analysis of semi-structured interviews (N = 37) focused specifically on student understanding of the elephant toothpaste reaction and making liquid nitrogen ice cream at a general chemistry level. Results show prevalent misunderstandings and misconceptions of the content despite the sample being composed primarily of junior and senior chemistry majors. Implications for teaching in both formal and informal environments are presented in light of these findings, as well as potential future investigations of the teaching and learning occurring during chemistry outreach.

KEYWORDS: Chemical Education Research, Public Understanding/Outreach, Upper-Division Undergraduate, Second-Year Undergraduate, Misconceptions/Discrepant Events, Catalysis, Phases/Phase Transitions/Diagrams, General Public

FEATURE: Chemical Education Research

INTRODUCTION

Informal Science Education

Over 80% of K−12 student learning occurs in informal learning environments (i.e., outside of the formal classroom); this number dramatically increases as students leave the K−12 environment.1 Given that the majority of learning occurs outside of the classroom, informal learning environments are uniquely situated to provide learning opportunities that may address growing concerns about public understanding of science.7 However, informal learning environments are much more complex and diverse as compared to formal learning environments.

Formal science learning environments are typically viewed as compulsory and in-the-classroom, with learning goals focused on content and state standards.1,3,4 Informal science learning environments, on the other hand, are considered much more voluntary and occur in a variety of settings, including interactions with the media (e.g., television, radio, Internet, video games), cultural institutions (e.g., museums, zoos, aquariums), structured out-of-school-time programs (e.g., afterschool youth programs, clubs), and even just everyday experiences.1,3−5 Additionally, the specific learning outcomes typically targeted in informal science environments are much more varied. While understanding of scientific content and knowledge is one area of focus for informal science learning, five other areas/learning goals are recognized by the informal science community: (1) sparking interest and excitement, (2) engaging in scientific reasoning/scientific practices, (3) reflecting on science and understanding of natural phenomena, (4) using the tools and language of science, and (5) identifying with the scientific enterprise.1,6 On top of both environment and learning goal diversity, additional levels of complexity that make informal science learning environments unique include various audience levels/types (from young children to adults) and discipline-specific content differences (e.g., chemistry, biology, physics).

Informal science learning has been a national focus in the United States since 1957 when the National Science Foundation (NSF) first conducted studies on public understanding of science, before creating a program specifically...
focused on funding research on public understanding of science in 1958. Since then, informal science education has grown with NSF funding for broader informal science education investigations (beginning in 1983), special issues in research journals focused on informal science (International Journal of Science Education in 1991, Science Education in 1997, Journal of Research on Science Teaching in 2002), and multiple National Research Council reports in 2009 and 2010 focused on general informal science education practices.5,6 While these are only highlights of the major events in informal science education, they illustrate an increased interest in informal science learning and research in the U.S. Despite such a focus on general informal science education, discipline-specific informal science education has only recently become a national focus, particularly in chemistry.

Informal Chemistry Education and Chemistry Outreach

In 2016, the National Academies published a report titled Effective Chemistry Communication in Informal Environments.7 This report was the first scholarly investigation that tried to characterize national informal chemistry education practices. With focus placed specifically on practicing chemists, the report identified goals these chemists have for informal chemistry education events, including focusing on public appreciation of chemistry, developing scientifically informed consumers, and encouraging the public to pursue careers in the chemical sciences. The report also discussed the chemistry content typically targeted during chemists’ informal events, including biochemistry and materials chemistry, the chemistry of everyday life, and environment-related topics like climate change.7 While the report is limited and only represents the views of a sample of the population of chemists conducting informal chemistry education, it was the first in-depth investigation of informal chemistry education practices despite the ubiquity of informal chemistry education within the chemical enterprise.

Recently, a previous study by the authors8 sought to characterize the practices of a population that was not included in the Effective Chemistry Communication in Informal Environments report: college students. College students affiliated with American Chemical Society (ACS) and Alpha Chi Sigma (AXΣ) student chapters reach almost 1 million people every year through their informal chemistry education events (typically termed chemistry outreach).9,10 With such a large number of people affected by their outreach, it was prudent to characterize the chemistry outreach practices of these college students. Results from a survey on college students’ and their faculty advisors’ goals for outreach indicate that these collegiate chapters of ACS and AXΣ have goals distinguishable from the chemists included in the 2016 National Academies reports7 the most prevalently discussed goal for college students and their faculty advisors is that their audiences learn chemistry content as a result of attending chemistry outreach events.8 Other goals include that the audience learns that science is fun, develops curiosity, and has fun/enjoys themselves. The most prevalently facilitated activities during these college students’ outreach events include the elephant toothpaste reaction (the catalytic decomposition of hydrogen peroxide into water and oxygen11,12) and making liquid nitrogen ice cream.13

These findings indicate that college students involved with chemistry outreach align their events with the general informal science learning goal of understanding scientific content and knowledge.1,6 As such, given the cognitive learning goals these college students have for their teaching during chemistry outreach events (i.e., audience learning chemistry content),8 it is timely to consider the role of content knowledge in the teaching and learning process for college students facilitating outreach. With little research in informal science education focused on the facilitator’s content knowledge as it pertains to achieving content-centered learning goals, it is necessary to consider research from formal learning environments.

Content Knowledge and Teaching

Researchers have considered how teachers in formal learning environments develop teaching knowledge since 1986 when Shulman coined the term pedagogical content knowledge (PCK).15 PCK refers to “subject matter knowledge for teaching”, or the knowledge and skills needed to successfully teach a specific subject.15,16 Since then, there have been multiple different interpretations of PCK, including refining it into discipline-specific (e.g., science), subject-specific (e.g., chemistry), and even topic-specific (e.g., equilibrium) levels.17,18 No matter the interpretation, all models emphasize the role of the teacher’s own content knowledge (CK) on the development of PCK: a teacher must understand the content in order to be able to teach it.16 Multiple investigations (across a variety of disciplines, subjects, topics, and instructional levels) have supported that CK is a necessary component for developing PCK, and the CK of the teacher has an impact on their teaching and student learning.19−24 Rollnick and colleagues25 best summarized the importance of teacher CK as it relates to student learning: “If teachers do not have in-depth knowledge of a topic themselves, it is clearly difficult for them to provide conceptual depth for their students.”

Despite the known relationship between CK and PCK, the exact connection between a teacher’s CK and how they develop PCK remains unclear; therefore, there is a need to explore teacher CK more in-depth to understand how CK leads to PCK.25,26 Although all CK and PCK studies have investigated formal classroom teachers (both in K−12 and university settings), the influence of CK on teaching transfers to informal environments where events align with the learning goal of understanding scientific content and knowledge. This is particularly important for college students conducting outreach, since their goals for outreach include the audience learning content. Therefore, investigating the CK of college students acting as informal educators/teachers is warranted to further understand the teaching and learning occurring in chemistry outreach.

RESEARCH QUESTIONS

With the connections among teaching skills, content knowledge, and student/audience learning, investigating the CK of these college students is necessary (particularly considering their most prevalent goal of chemistry outreach is audience learning). Therefore, the study described in this paper seeks to address the following research questions (RQs): For college students conducting chemistry outreach, what is the nature and extent of their content knowledge associated with (1) the elephant toothpaste reaction? and (2) making liquid nitrogen ice cream?

METHODS

As part of an Institutional Review Board approved study on chemistry outreach practices, semi-structured interviews27 were conducted with college student outreach practitioners
associated with ACS and AXΣ student chapters throughout spring 2016 to spring 2017. As this population was dispersed across the United States, multimedia-based programs (e.g., Skype, Google Hangouts) were used to contact participants and to conduct the interviews. The interview protocol was structured in four phases: (1) demographics and purpose(s) of conducting chemistry outreach, (2) criteria for successful outreach events, (3) understanding of chemistry content embedded in outreach activities, and (4) training and skills development. Interviews conducted over this platform successfully elicited useful data that has been shown to yield trustworthy conclusions. For the purpose of this paper, only data from phase 3 (chemistry content) will be presented, as it directly addresses the research questions above. Included in the Supporting Information are questions from the interview guide for phase 3.

Sample

Using a variety of recruitment efforts, including in-person recruitment and emails to gatekeepers, a total of 37 college student outreach practitioners were sampled and interviewed as part of this study. The sampled students were from 22 geographically diverse institutions across the U.S.A., with small primarily undergraduate institutions to large research-intensive institutions represented. Participant demographics included a mixture of males (n = 17) and females (n = 20), chemistry/biochemistry majors (n = 22), other science majors (n = 11), nonscience majors (n = 2), and chemistry graduate students (n = 2). The undergraduate students in the sample included sophomores/second years (n = 5), juniors/third years (n = 11), and seniors/fourth or fifth years (n = 19). Since this study targeted the population of ACS and AXΣ student chapter members who had previous experience conducting chemistry outreach before, it is not surprising that the interviewed sample was composed primarily of upper-division chemistry/biochemistry majors. A table that disaggregates the sample demographics by participant is included in the Supporting Information. In addition, in congruence with demographic data as outside of the scope of the research questions addressed herein.

Because the prompt asked students to critique individual statements/lines of the general chemistry level explanations, a content analysis was performed by analyzing student responses to these individual statements. The analysis coded student responses as (1) identified the content as correct, (2) identified the content as incorrect, or (3) made no comments about the accuracy of the content. The breakdown of the inaccurate explanations into individual statements is shown in Table 1 (elephant toothpaste) and Table 2 (making liquid nitrogen ice cream). Once student ideas about each statement were coded, patterns and trends were investigated by looking within and between students using the demographic data as grouping criteria. Responses were analyzed to see if major, gender, year in school, and/or school size had any relationship with student responses/understanding of the chemistry content.

<table>
<thead>
<tr>
<th>Number</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>This reaction involves the catalytic decomposition of hydrogen peroxide into water and hydrogen gas.</td>
</tr>
<tr>
<td>2</td>
<td>This acid–base reaction is...</td>
</tr>
<tr>
<td>3</td>
<td>...an exothermic reaction because bonds are broken and heat is released.</td>
</tr>
<tr>
<td>4</td>
<td>A catalyst is used because the decomposition is not spontaneous.</td>
</tr>
<tr>
<td>5</td>
<td>The catalyst allows the reaction rate to increase because the mechanistic pathway changes.</td>
</tr>
<tr>
<td>6</td>
<td>The catalyzed mechanism has two steps with higher activation energies.</td>
</tr>
<tr>
<td>7</td>
<td>Overall, the catalyst decreases the overall enthalpy change of the reaction.</td>
</tr>
<tr>
<td>8</td>
<td>The reaction starts off slow because the first step is the rate limiting step.</td>
</tr>
<tr>
<td>9</td>
<td>Soap is used to help break down the hydrogen peroxide.</td>
</tr>
<tr>
<td>10</td>
<td>Once all of the catalyst is converted to the intermediate, the reaction dramatically speeds up as noted by the increase in foam being produced.</td>
</tr>
<tr>
<td>11</td>
<td>Since the products are gas, the foam expands as the gas molecules inside the foam spread out.</td>
</tr>
</tbody>
</table>

“Inaccurate chemistry content is bold for clarity (adapted from Pratt and Yezierski, 2018).”
Table 2. Statement Breakdown of General Chemistry Level Inaccurate Explanation of Liquid Nitrogen Ice Cream

<table>
<thead>
<tr>
<th>Number</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The ice cream solution is a mixture of milk, sugar, and flavoring and milk is primarily composed of water.</td>
</tr>
<tr>
<td>2</td>
<td>Dissolving the sugar into the milk increases the freezing point of the milk causing it to freeze at a higher temperature.</td>
</tr>
<tr>
<td>3</td>
<td>Nitrogen is a gas at room temperature because of strong intermolecular forces between the nitrogen molecules (London dispersion interactions).</td>
</tr>
<tr>
<td>4</td>
<td>Liquefying nitrogen requires low temperature and high pressure in order to decrease the kinetic energy/slow down the molecules enough to have the intermolecular forces take hold.</td>
</tr>
<tr>
<td>5</td>
<td>As soon as the liquid nitrogen’s container is opened, it boils because the vapor pressure of liquid nitrogen is so high.</td>
</tr>
<tr>
<td>6</td>
<td>During boiling, the temperature of the liquid nitrogen increases as it changes to a gas.</td>
</tr>
<tr>
<td>7</td>
<td>Heat from the ice cream solution is absorbed by the liquid nitrogen.</td>
</tr>
<tr>
<td>8</td>
<td>Because the temperature difference between the ice cream solution and the liquid nitrogen is so great, the transfer of heat is very fast allowing for the ice cream to freeze almost instantly.</td>
</tr>
<tr>
<td>9</td>
<td>The water inside the ice cream mixture goes from a liquid state to a solid state because heat is lost and the molecules slow down creating solid ice cream.</td>
</tr>
</tbody>
</table>

“I inaccurate chemistry content is bold for clarity (adapted from Pratt and Yezierski, 2018).”

Trustworthiness

As with all qualitative studies, it is necessary to provide evidence for the trustworthiness of conclusions by evaluating the data collection and analysis (similar to the validity and reliability of quantitative studies). The data-driven design of this study, as well as a previously published case study analysis of the data collection techniques for successful elicitation of student ideas, provides evidence for the trustworthiness of the data obtained. Additionally, the increased sample diversity, both in terms of institution type/size and student demographics, adds trustworthiness to the resulting conclusions from this study in the form of increased transferability. While such holistic approaches support the rigor of the data collection, the content analysis performed was also subjected to steps that support the confirmability and dependability of the findings. These steps included initially treating each student as a case in order to categorize their initial responses to each statement, as well as any revisions to their responses that occurred later in the interview. Analysis within and between students also adds trustworthiness as it allowed for any patterns or trends to emerge due to demographics rather than individual chemistry understanding. Throughout the project, weekly debriefing sessions with the two researchers allowed for the team to come to consensus on unique cases/responses, and to collectively determine future analytic steps. Additionally, peer scrutiny with CER colleagues at the same institution (not involved with the project), and with those attending national research conferences, ensured that the research team’s interpretations of data and presentation of findings were rigorous. All of the aforementioned techniques, as well as the inclusion of a copy of the interview guide questions in the Supporting Information, add transparency to the data collection and analyses, which augments the overall trustworthiness of the data presented and resulting conclusions.

RESULTS

RQ 1: Chemistry Understanding of the Elephant Toothpaste Reaction

Of the college students interviewed as part of this study (N = 37), only 26 had previous experience conducting the elephant toothpaste experiment and critiqued the inaccurate general chemistry explanation during the interview. To clarify the analysis, the explanation was subdivided into chemically correct statements (Table 3) and chemically incorrect statements (Table 4); representative student quotations for when a student said the chemistry was correct or incorrect for each statement are provided in both tables.

Of note are the differences in quotation lengths when a student believed the statement to be correct vs incorrect. When a participant said the statement was correct, they rarely expanded on their ideas as evidenced by the short, succinct quotations. However, when a student said the statement was incorrect, they tended to elaborate and explain why they believed the chemical idea was inaccurate, leading to longer excerpts.

To capture the frequency of students agreeing/disagreeing with the chemistry content and to understand which statements/chemical ideas students prevalently struggled with, the data were visualized. Separate graphs were constructed for the correct statements and incorrect statements (see Figure 1). In both graphs, green signifies students correctly identifying the content as accurate or inaccurate (i.e., evidence that the student understands the chemical concepts). Red is used when student responses about the accuracy/
inaccuracy of the statements were incorrect (i.e., evidence of students misunderstanding the chemical concepts and/or having misconceptions). Despite the prompt asking students to discuss the accuracy of each line/statement, some students did not provide a response that critiqued the accuracy of the content in every statement (i.e., provided no evidence of their understanding of the chemistry content); these responses are represented by gray dots. Such responses in which students did not comment on the accuracy of the statements typically occurred when a student read two statements back-to-back, but only critiqued the second/final statement's accuracy. While the interviewer attempted to have students go back and critique these overlooked statements, there was a concern that overprompting the students would cause them to think statements were incorrect solely because the interviewer was asking the students to relook at them. In addition, while some students were critiquing individual statements, additional inaccurate chemical concepts were elicited; because these inaccurate ideas were separate from those included in the statements, these ideas were excluded from the graphs and tables.
included in Table 5. Despite the limitation in eliciting ideas (i.e., the gray dots where students provided no comments about the accuracy of statements), the majority of the participants provided critiques for every statement. Only one statement (statement 8) had a higher number of students who did not comment on the accuracy of the content than those who did critique the content accuracy. Additionally, since these statements elicited other inaccurate ideas not included in the statements, additional evidence for the trustworthiness of the data obtained is provided. These additional inaccurate ideas also add to the rich description of students’ conceptual chemistry understanding as it relates to the elephant toothpaste reaction.

RQ 2: Chemistry Understanding of Making Liquid Nitrogen Ice Cream

Of the college students interviewed as part of this study (N = 37), only 15 had previous experience making liquid nitrogen ice cream and critiqued the inaccurate general chemistry explanation during the interview. Similar to the analysis of responses to elephant toothpaste, student responses to making liquid nitrogen ice cream were subdivided by the accuracy of the statements: chemically correct statements in Table 6 and chemically incorrect statements in Table 7. Included in both tables are representative student quotations for when a student said the chemistry was correct or incorrect.

### Table 6. Representative Student Responses to Chemically Correct Statements in the General Chemistry Level Explanation for Liquid Nitrogen Ice Cream

<table>
<thead>
<tr>
<th>Statement Number</th>
<th>Representative Quotation When Student Said Chemistry Was Correct</th>
<th>Representative Quotation When Student Said Chemistry Was Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>“That’s all true. I like that. We just add vanilla so I guess that’s their flavoring.” (Helena, sophomore chemistry major)</td>
<td>n/a</td>
</tr>
<tr>
<td>4</td>
<td>“Yep I agree with that sentence” (Neena, junior chemistry major)</td>
<td>n/a</td>
</tr>
<tr>
<td>5</td>
<td>“I think that sounds good, I would draw pictures... also. If they have like a board.” (Ooro, chemistry graduate student)</td>
<td>n/a</td>
</tr>
<tr>
<td>7</td>
<td>“HEAT TRANSFER! Yes!!! [laughter] Good! Yes! This is how I would word it!” (Mary Jane, sophomore chemistry major)</td>
<td>“The temperature of the nitrogen is increasing because the cold is going to the ice cream, and nitrogen’s increasing” (Lana, junior chemistry major)</td>
</tr>
<tr>
<td>8</td>
<td>“Yes, causing ice cream to freeze instantly, which I tried to hit [on] earlier” (Edwin, senior chemistry major)</td>
<td>n/a</td>
</tr>
<tr>
<td>9</td>
<td>“Sure. Sounds good.” (Pamela, senior science major)</td>
<td>n/a</td>
</tr>
</tbody>
</table>

### Table 7. Representative Student Responses to Chemically Incorrect Statements in the General Chemistry Level Explanation for Liquid Nitrogen Ice Cream

<table>
<thead>
<tr>
<th>Statement Number</th>
<th>Representative Quotation When Student Said Chemistry Was Correct</th>
<th>Representative Quotation When Student Said Chemistry Was Incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>“Yaaas! Increases the freezing point! Yaaas! That’s good cause that’s a thing they learn!” (Mary Jane, sophomore chemistry major)</td>
<td>“Hold on. The part... I think that’s wrong... I think it actually decreases the freezing point rather than increases it.” (Reggie, junior chemistry major)</td>
</tr>
<tr>
<td>3</td>
<td>“I feel like that’s missing the point of this specific demo... it’s a good additive... it’s perfectly fine.” (Max, junior chemistry major)</td>
<td>“When molecules have strong intermolecular forces, doesn’t it mean it’s a solid?... Yea. I feel like strong intermolecular forces is a property of a solid because that means when the... when there’s a strong force between molecules, there’s limited... movement... makin’ it a solid.” (Beatriz, sophomore chemistry major)</td>
</tr>
<tr>
<td>6</td>
<td>“Which makes sense because it absorbs energy from the surroundings.” (Johnny, junior chemistry major)</td>
<td>“Technically that’s wrong... technically as you’re changing from a liquid to a gas... the temperature does NOT change.” (Steve, senior chemistry major)</td>
</tr>
</tbody>
</table>

Figure 2. Line-by-line analysis of student responses to general chemistry level explanation of liquid nitrogen ice cream (n = 15). Green is evidence of students understanding the chemistry content; red is evidence of students misunderstanding the chemistry and/or having misconceptions.
Table 8. Other Inaccurate Chemical Ideas Elicited from Students When Responding to Liquid Nitrogen Ice Cream Statements

<table>
<thead>
<tr>
<th>Statement Number</th>
<th>Inaccurate ideas</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>“I also think it would be... good to... cause people don’t think of like... oh I’m going to open it and it’s going to boil because of the vapor [pressure]... like they might not know that vapor pressure can make it boil... you could say something like... vapor pressure or like temperature can like make it do that. Much like when you boil water on the stove, you increase the temperature” (Lana, junior chemistry major)</td>
</tr>
<tr>
<td>7</td>
<td>“Technically the—liquid nitrogen is undergoing uh— an endothermic reaction cause it’s absorbing the heat. So—I would use endothermic and exothermic and stuff like that. They should know that at this level—[say] “the liquid nitrogen’s undergoing an endothermic reaction cause its absorbing heat. It sounds more scientific and they should be able to understand it at that level.” (Orozo, chemistry student)</td>
</tr>
</tbody>
</table>

Just as with the responses to the statements about elephant toothpaste, student responses about liquid nitrogen ice cream were visualized to ascertain frequencies of responses (see Figure 2). The same color scheme was used: green for when students correctly identified the content as accurate or inaccurate, red for when student responses about the accuracy/inaccuracy of the statements were incorrect, and gray dots for when students did not provide a response that critiqued the accuracy of the content. Likewise, some statements from the liquid nitrogen ice cream explanation elicited additional inaccurate ideas from the students that were not included in the graphs; these ideas are included in Table 8.

■ DISCUSSION

RQ 1: Chemistry Understanding of the Elephant Toothpaste Reaction

As shown in Figure 1A, the majority of the students were able to successfully identify statements containing accurate chemistry content as correct (statements 5, 8, 10, and 11). However, there were instances for all four correct statements in which at least one student indicated that they believed the content was incorrect (despite it being chemically accurate). Of pressing concern are statements 5 and 10, which both discusses general changes to the reaction mechanism when a catalyst reacting to form an intermediate. Four students said statement 5 was incorrect and that a catalyst only lowers the activation energy of a reaction; it does not change the mechanism. Carrie’s quotation in Table 3 is representative of these responses. This idea is a published student misconception regarding kinetics and catalysis.32 For statement 10, seven students said that the chemical idea was incorrect by stating that a catalyst does not change during a reaction. Sue’s quotation in Table 3, as well as this quotation by Shayera, best illustrate these students’ ideas: “The catalyst is not being converted to anything. It stays the same. That’s the whole point of a catalyst” (Shayera, senior chemistry major). Once again, this is also a published misconception on student understandings of kinetics and catalysis.33 While those familiar with the misconceptions literature may not be shocked by junior and senior chemistry/biochemistry majors having misconceptions related to kinetics and catalysis, the concern is that these students are acting as informal chemistry educators/teachers during chemistry outreach events without chemically accurate understanding of the chemistry they are teaching. This becomes even more alarming when the inaccurate statements related to elephant toothpaste are considered.

The graph in Figure 1B of student responses to chemically inaccurate statements about the elephant toothpaste reaction shows a much larger proportion of students coded as red, meaning that they believe the chemically inaccurate statements are actually scientifically accurate. For every inaccurate statement, at least three students indicated that the statements were correct. Statement 1, which targets students’ understanding of the products of the elephant toothpaste reaction, had 12 students indicate that the products of the reaction are water and hydrogen, rather than the correct products of water and oxygen. Statement 2 focuses on how students classify the reaction, and six students supported, inaccurately, that the reaction was an acid–base reaction, while an almost equal number (n = 7) knew that the reaction was not an acid–base reaction. Oliver and Helena’s quotations in Table 4 are representative of these student responses. Even though these seven students knew that it is not an acid–base reaction, only one student was able to correctly classify the reaction as an oxidation–reduction reaction. The remainder were only able to state that it was not an acid–base reaction. Both statements 1 and 2 are factual statements that primarily junior and senior chemistry/biochemistry majors should know. The tasks of predicting the products of a reaction and classifying the reaction type are very common in the general chemistry curriculum and should be easy for students nearing graduation with a chemistry degree. However, despite this, some students were unable to reason about the reaction type and felt unconfident doing so, as shown by a quotation from Merina (senior chemistry major). “I’ve never fully been very confident in acid–base reactions in... my entire chemistry experience... I don’t like classifying reactions as anything because I usually get them wrong.” While upper-division chemistry students struggling with general chemistry content is concerning, what is more pressing is that these college students are acting as informal educators and should understand these ideas before teaching them to children/younger students. This also raises a pressing safety concern. These college students/chemistry outreach practitioners may not know the reactants involved, products made, or type of reaction occurring, and yet they are performing the reactions with a vulnerable population where they must assume responsibility for the safety of all of those attending the event.

Statement 3 was by far the most frequently misunderstood statement that students discussed; it targets the prevalent misconception of exothermic bond breaking.16,34 Fourteen students supported the idea that breaking bonds releases

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energy, such as the response by Helena in Table 4. Given the
prevalence of this misconception in the literature, it is not
surprising that students in this sample evidenced this
inaccurate idea. However, it should concern chemistry
educators that this sample has a variety of experiences,
comes from a variety of institutions/locations, and yet there
were no trends based on the demographic information to
suggest that certain schools/types, majors, etc. were the ones
that had this misconception. This provides further support of
the prevalence of this misconception across the country/
different chemistry programs. Additionally, while an inves-
tigation of the type of formal instruction these college students
had is out of the scope of this paper, this result may support
the calls for active learning pedagogies36 and curricular reforms
that may promote conceptual understanding and minimize
misconceptions (such as those by Cooper and Klymkowsky,37
Sevian and Talanquer,38 or the emphasis on three-dimensional
learning from the National Academies39).

Statements 4, 6, and 7 all target student ideas of
thermodynamic concepts related to catalyzed reactions
(including spontaneity, activation energy, and enthalpy). For
all three statements, 19−35% of students in the sample
evidenced misconceptions of these thermodynamic concepts.
With the numerous publications discussing students struggling
to understand thermodynamics (including having misconcep-
tions),40 these results are not surprising. Additionally, other
inaccurate ideas were elicited from a few students (see Table
5). While these ideas are idiosyncratic, they show misunder-
standings and misconceptions not previously discussed in the
literature. These add to the rich description of these college
student outreach practitioners’ chemistry understanding/
misunderstanding that they are bringing to their teaching in
outreach, particularly related to kinetics and thermodynamics.

One limitation of the data collection technique was that
some students would not provide a critique of the accuracy of
the content in every individual statement (i.e., the gray dots in
Figure 1). While it may not be concerning when this occurs for
chemically accurate statements, it is concerning that there were
students not critiquing the accuracy of the chemically
inaccurate statements. While we cannot comment on whether
or not these students hold the inaccurate ideas embedded in
these statements, Meaningful Learning theory41,42 provides a
lens that helps us draw some conclusions about these students’
chemistry understanding. Meaningful Learning is a type of
Constructivism43,44 that differentiates rote learning (e.g.,
memory of isolated ideas) from meaningful learning
(e.g., meaningfully linked ideas)41,42. Figure 3 provides a visual
representation that differentiates rote learning from meaningful
learning. One requirement of meaningful learning is that a
student must actively choose to learn meaningfully and not
memorize/rote learn.41,42 If a student had meaningfully learned
the chemistry content embedded in the inaccurate statements,
reading the statements would prime the connections in their
mind and they would recognize the inaccuracies. However, if a
student rote learned the material, there are likely no
connections (or nonmeaningful, incorrect connections)
between ideas, and the student would likely not recognize
the inaccuracies. Therefore, it is possible that the students who
read the inaccurate statements and did not critique the
accuracies of the content may have rote learned the material
since no connections were primed to signal the students to the
inaccuracies in the statements. Additionally, some students
during the interview openly admitted to not knowing the

![Rote Learning vs Meaningful Learning](image)

**Figure 3.** Representation of rote learning vs meaningful learning; individual circles represent unique chemical ideas, and lines represent meaningful connections between ideas.

chemistry or not choosing to learn it (n = 13). For example,
while discussing the statements about elephant toothpaste,
Oliver (senior science major) said, “I don’t know. I’m not an
expert in any of these reactions”, and Merina (senior chemistry
major) said, “I don’t know… Oh man! This is bad because I tutor
so often too!” Students who admitted to choosing not to learn
the chemistry include Remy (senior science major) who said,
“It was never a priority of mine to, to know like exactly what’s
going on.” These quotations support that these students may
have chosen to meaningfully learn the chemistry content
and, therefore, support rote learning as a lens that may explain
why some students chose to make no comments about the
accuracies of some of the statements.

Last, the data were analyzed for patterns and trends by
comparing student responses to school characteristics and
student demographics. No patterns or trends emerged from
this analysis. The responses were varied, and no individual
students were getting every statement right/wrong. Surpris-
ingly, some students were inconsistent even in their own
responses. For example, consider statements 5 and 10, which
both target the role of a catalyst in the mechanism of the
reaction. We would predict that if a student believed that the
mechanism did not change upon the addition of a catalyst (i.e.,
saying statement 5 is incorrect), they would then also say that
the catalyst does not convert to an intermediate (i.e., saying
statement 10 is incorrect). However, we found that four
students were inconsistent and saying statement 5 was correct
while statement 10 was incorrect, or vice versa. This further
supports the rote learning suggested for the no comment
responses. If students are not learning meaningfully, then they
may not have meaningful connections between related
chemical ideas (like a catalyzed mechanism and an
intermediate involving the catalyst). Therefore, it would not
be surprising if a student did not see the connection between
mechanism (statement 5) and forming an intermediate
(statement 10), as we see in this study.

**RQ 2: Chemistry Understanding of Making Liquid Nitrogen Ice Cream**

Student responses to the statements about making liquid
nitrogen ice cream are strikingly different than those for the
elephant toothpaste reaction (see Figure 2). First and
foremost, there was only one instance of a student saying
that a chemically correct statement was actually inaccurate
(statement 7). In this instance, the student discussed the flow of
cold from liquid nitrogen to the ice cream mixture, rather
than the flow of energy in the form of heat from the ice cream mixture to the liquid nitrogen (see Table 6). For all other chemically correct statements, students either recognized the accuracy of the content or made no comments about the accuracy. This is likely due to the differences in the content embedded in the elephant toothpaste reaction vs making liquid nitrogen ice cream. The elephant toothpaste reaction is a complex reaction involving thermodynamic, kinetic, and catalytic considerations, which are all included in the statements that the students critiqued. Additionally, there are many published misconceptions related to thermodynamics and kinetics illustrating the difficulty students have learning these ideas.40,41 On the other hand, making liquid nitrogen ice cream does not involve a complex reaction; it is two concurrent phase changes (liquid-to-solid for the ice cream mixture and liquid-to-gas for the nitrogen) due to the transfer of energy between the ice cream and liquid nitrogen. Misconceptions related to phase changes are primarily due to misunderstanding the particulate nature of matter,43 which was not explicitly evaluated in the statements written about making liquid nitrogen ice cream. These content differences, along with the smaller sample of students critiquing the statements regarding making liquid nitrogen ice cream, may explain these performance differences. However, when considering the inaccurate statements related to making liquid nitrogen ice cream, there are still concerns about student understanding that are worth discussing.

For all three chemically inaccurate statements, approximately equal numbers of students indicated that the content was correct and incorrect. For statement 2, which assesses the impact of a solute on a freezing point, seven students indicated that freezing point elevation was chemically correct, while six recognized that it should be freezing point depression. Statement 3 assesses student understanding of the structure–property relationship between intermolecular forces and state of matter; six students indicated that London dispersion interactions were strong interactions, while seven indicated that London dispersion forces between nitrogen molecules are relatively weak. Lastly, statement 6 assesses how temperature changes (or does not change) during a phase change. Three students indicated that temperature increases during a phase change, while only four students knew that temperature remains constant during a phase change. The remainder of the students made no comments about the accuracy of the statement.

The content embedded in all three chemically inaccurate statements is well-aligned with instruction in first-year general chemistry courses. Considering that almost half of the sample evidenced misunderstandings of statements 2 and 3, and over half did not comment on the accuracy of statement 6, instructors and those seeking out these college students to conduct chemistry outreach should be concerned. The assumption that passing a course indicates that students learned/memorized facts, but did not meaningfully learn (i.e., did not connect the fact that London dispersion interactions between nitrogen molecules are relatively weak to ideas like polarity, disruption of the electron cloud, or instantaneous and induced dipoles). Just as with responses to the elephant toothpaste reaction, additional inaccurate ideas were elicited by some of the statements about making liquid nitrogen ice cream (Table 8). While these ideas are idiosyncratic, all additional inaccurate ideas were elicited by chemically correct statements; this adds to the rich description of student ideas related to making liquid nitrogen ice cream, supports the task as a successful elicitation tool, and helps to ensure the trustworthiness of the findings. In addition, these additional inaccurate ideas further provide evidence that these upper-division students struggle with thermodynamic concepts (shown by the quotations from Ooro and Helena in Table 8).

Patterns and trends were investigated by comparing student responses to making liquid nitrogen ice cream statements to school characteristics and student demographics. Once again, no patterns or trends emerged from this analysis. While this may be due to the small sample size (n = 15), this also supports the Constructivism/meaningful learning41–44 lens applied to the data. If students are constructing their own knowledge, then it is not surprising that no patterns were found. All of the students had unique backgrounds, came from a variety of institutions, and therefore had varying prior knowledge. The likelihood that students would construct their knowledge in the same way is highly unlikely. Additionally, with the evidence that supports that students may be rote learning/memorizing, the lack of patterns or trends in responses is expected.

### CONCLUSIONS

Presented in this study is evidence that college student outreach practitioners have misconceptions and misunderstandings related to the elephant toothpaste reaction and making liquid nitrogen ice cream, despite having previous experience facilitating these activities with children/younger students and passing a college general chemistry course. Specifically for the elephant toothpaste reaction (RQ 1), the majority of the students did not know the products of the reaction, and evidenced published misconceptions related to catalysis and bonding/thermodynamics. For making liquid nitrogen ice cream (RQ 2), the students were more successful in their discussion of chemistry. However, approximately half of the students struggled with the general chemistry concepts.
of freezing point depression and ideas related to intermolecular forces.

Across both activities and investigations of the research questions, students provided evidence that suggests these students are memorizing/rote learning chemistry content during their undergraduate coursework. Considering that the content students discussed was written to align with the level of college general chemistry, and that a majority of the students in the sample were third- and fourth-year undergraduates, this is most concerning. Additionally, these students are in teaching roles during their outreach events and believe that teaching and learning are important goals/success criteria for their events. The fact that these students evidence misunderstandings and common misconceptions (i.e., inaccurate content knowledge) poses concerns about the quality of outreach instruction and what younger students/children may be actually learning during these events.

**LIMITATIONS**

While these findings suggest a need to look critically at outreach practices and formal instruction of undergraduate chemistry students, this study has several limitations. First and foremost, despite the total sample size (N = 37) being based on data saturation, the subsample sizes for elephant toothpaste (n = 26) and making liquid nitrogen ice cream (n = 15) are small. While this may detract from potential transferability of the findings, the increased sample diversity, which has not been seen before in previous in-depth qualitative studies in CER, helps alleviate this concern. Additionally, it is possible that the demographics of the sample do not transfer to all outreach practitioners. Another limitation, as noted in the discussion, is that there were many instances where students chose not to provide comments about the accuracy of some of the statements. While this limits the conclusions that can be drawn about the overall sample, the lack of patterns or trends in responses (including no single students being the ones not providing comments) suggests that the task was mostly successful in eliciting student ideas. This, combined with the elicitation of other idiosyncratic incorrect chemical ideas, adds to the rich description of student ideas and supports the conclusions drawn about student understanding of the elephant toothpaste reaction and making liquid nitrogen ice cream. Lastly, it is important to note the differences in the explanations/prompts between the elephant toothpaste reaction and making liquid nitrogen ice cream. Approximately a third of the elephant toothpaste statements and two-thirds of the liquid nitrogen ice cream statements were chemically correct. This difference in the ratio between chemically correct vs incorrect statements embedded in the critiqued explanations poses limitations in the conclusions that can be drawn from comparing data from elephant toothpaste to that from liquid nitrogen ice cream. Combined with the subsample size differences mentioned above, it is important that readers not draw many conclusions that relate elephant toothpaste findings with liquid nitrogen ice cream findings. Rather, conclusions should be made about student understanding of content underlying elephant toothpaste and liquid nitrogen ice cream separately, aligned with the structure of this paper.

**IMPLICATIONS**

The findings presented have important implications for teaching and learning in chemistry. Because the sample includes a variety of institutions, and likely instruction types, the prevalence of misconceptions found in this study (including exothermic bond breaking) suggests a need for increased dissemination of the misconceptions literature and curricular reform efforts. Additionally, because of the goal these college student outreach practitioners have of *audience learning* during outreach, a close examination of what children/younger students are actually learning and taking away from their outreach experiences is needed. Outreach planners, including faculty soliciting college student organizations for outreach experiences, must carefully consider their desired goals for outreach events and how those are achieved by those facilitating the events. As teacher content knowledge is related to having the skills to successfully teach the content, the likelihood that younger students/children are actually learning during these events is low. Considering the number of misconceptions these college students may be bringing to their outreach teaching, it is further likely that if younger students/children are learning during these events, they are learning the misconceptions of the college students rather than accurate chemical concepts. Additionally, the assumption that “if a college student passed a course, they know the chemistry content” must be challenged. College students must carefully consider their goals for outreach events, the training they have in teaching and learning, and how well they understand the chemistry embedded in the activities they are facilitating. Becoming aware of the connection between CK and PCK is one step in improving college student training for teaching and learning in outreach, which may help to improve the impacts of their informal chemistry teaching.

For researchers, these findings support expanding qualitative studies to include multiple institutions for increased sample diversity. By increasing the diversity of samples included in investigations of student understanding of chemistry, qualitative studies can shed light on student understanding that crosscut institutional and instructional contexts. Additionally, on the basis of the findings presented in this study, targeted interventions focused on kinetics, thermodynamics, and catalysis implemented across multiple institutions are needed. Last, since these college students focus on their audiences learning chemistry, investigations of younger students/children attending outreach events and the resulting learning are needed. Such investigations are warranted because evidence from formal learning environments suggests that teachers with misconceptions pass them on to their students, which likely transfers to instruction in informal settings.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.8b00688.

Interview guide questions from phase 3 of the interviews focused on understanding of the chemistry content and a table disaggregating sample demographics by pseudonym (PDF, DOCX)
analyses and advice on data visualizations. We also thank chairs and faculty advisors who helped provided access to the participated in our study. We also acknowledge the department not know about science. http://www.pewinternet.org/2015/09/10/Press: Washington, DC, 2009.


Collegiate Organizations

Important?

REFERENCES

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Notes

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REFERENCES


