Bridging the Gap in Chemistry Education: The Role of Three-Dimensional Learning

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Understanding complex concepts in chemistry can be challenging for students, especially in large classes where individualised attention is limited. Traditional multiple-choice questions often focus on rote memorisation rather than deep understanding. Dr Sonia Underwood and colleagues at Michigan State University, Grand Valley State University, and Kansas State University, as part of the 3DL4US project, have developed a novel approach to create multiple-choice questions aligning with three-dimensional learning principles. This collaboration brings together a wealth of expertise and perspectives of chemistry, biology, and physics faculty who encourage students to engage with material deeper, promoting better comprehension and retention of core concepts.

The Need for Deeper Learning in Chemistry

Like many STEM fields, chemistry education has long struggled with how best to facilitate deep learning. Dr Sonia Underwood and colleagues recognised that traditional assessment methods were insufficient in promoting the critical thinking skills necessary for students to truly understand and apply chemical principles. Instead, they needed an approach that integrated core ideas, scientific practices, and crosscutting concepts – the three pillars of three-dimensional learning (3DL). This framework, proposed in the National Academies report *A Framework for K-12 Science Education*, aims to help students develop transferable knowledge and skills.

Understanding the Core Ideas, Integrating Scientific Practices, and Applying Crosscutting Concepts

Core ideas are fundamental principles that form the foundation of a discipline. In chemistry, these include the ideas of energy changes, atomic and molecular structure and properties, electrostatic and bonding interactions, and change and stability in chemical systems. These core ideas are essential because they explain multiple phenomena, predict outcomes, and generate new questions and insights. By focusing on these core ideas, educators can help students build a robust understanding of chemistry that goes beyond memorising isolated facts.

Scientific practices involve the skills and processes that scientists use to investigate the natural world. These include practices such as developing models, designing experiments, analysing data, and constructing explanations. Integrating these practices into chemistry education helps students learn how to think like scientists. They become more adept at applying their knowledge to solve problems and understand complex phenomena.

Crosscutting concepts are lenses (or tools) to help explain phenomena that span multiple scientific disciplines. These include ideas such as patterns, cause and effect, and systems and models. By teaching students to recognise and apply these concepts, educators can help them make connections between different areas of science. This holistic approach enhances their ability to understand and explain the world around them.

Developing 3DL-Aligned Multiple-Choice Questions

Often, instructors for large introductory courses rely on multiple-choice questions for assessment purposes. While open-ended questions for assessment that require students to write and draw are best, Dr Underwood and her colleague Dr Alexandria Roach propose an approach for how to improve standard multiple-choice questions to align with 3DL that are scaffolded and centred around specific chemical phenomena. First, the team identifies the focus of the cluster set, which can be key concepts students find challenging or a phenomenon the instructor wants the students to explore (i.e., select a topic or phenomenon relevant to the core ideas of chemistry). Next, the team outlines the specific knowledge students should demonstrate towards the chosen topic or phenomena (sometimes referred to as knowledge statements or evidence statements). The final step is developing a series of questions that target this specific knowledge while collectively aligning with the 3DL framework to engage students in scientific practices and apply crosscutting concepts.

For example, the team built a series of scaffolded multiple-choice questions related to thermochemical reactions to elicit students' understanding of the core ideas of energy changes and electrostatic and bonding interactions in chemistry (Figure 1). With this example, the questions developed focused on students interpreting reaction energy diagrams and their understanding of energy changes in reactions, particularly through the role of

energy in bond breaking and forming. Each question is designed to build on the previous one, ensuring a cohesive and comprehensive assessment to not only test students' knowledge but also engage them in scientific practices and crosscutting concepts.

Once the questions were developed, rigorous pilot testing occurred, which involved administering the questions to students in various educational settings and analysing their responses. The team uses these data to further refine the questions, ensuring that they effectively assess students' understanding and align with the 3DL framework. This method provides instructors with a more comprehensive assessment of each student's knowledge and ability to use it in various contexts.

Insight gained from 3DL multiple-choice cluster sets

Dr Underwood and Dr Roach tested the 3DL cluster shown in Figure 1 by applying it across various educational settings. The goal with the various applications was to gain insight into how 3DL-aligned multiple-choice questions can provide critical information regarding 1. Student learning across their degree programme using traditional chemistry curricula, 2. Understanding of the impact on student learning for students enrolled in a transformative 3DL-aligned general chemistry curriculum, and 3. how the impact persists across multiple institutions.

The first application examined chemistry/biochemistry majors at different stages of their chemistry education, from introductory courses to graduating seniors, to provide insights into how student understanding of chemistry evolved throughout the academic journey. Ideally, student understanding of chemistry core ideas is expected to grow as they progress through their undergraduate chemistry/biochemistry degree so that students in higher academic levels perform better than their counterparts in lower levels. The data trends in Figure 2 begin to tell another story and highlight how 3DL-aligned multiple-choice cluster sets can shine a light on student knowledge growth or lack thereof as they progress through a degree program. The team found that while most students, regardless of position in their degree progress, could identify an exothermic reaction diagram – Question 1 (Figure 1), many struggled with understanding the energy dynamics of bond breaking and forming for Question 2 and deeper reasoning in Question 3. This underscores the need for continuous refinement of instructional methods as students were found to have difficulty correctly applying their chemistry knowledge, regardless of position in the degree programme.

The second application compared STEM majors enrolled in General Chemistry 2 at two institutions using a 3DL-aligned curriculum (*Chemistry, Life, the Universe and Everything* – CLUE) to their peers within the same institutions using traditional curriculum materials. Often, commercially available curricula materials like those used in the institutions' Original curricula do not consist of content and assessments designed in a manner that draws explicit connections among core ideas, scientific practices, and crosscutting concepts. The data trends in Figure 3 support the claim that students taught using a 3DL-focused curriculum performed significantly higher than their peers in the Original General Chemistry 2 curriculum, which is not 3DL-focused. This means that CLUE students had a better grasp of core concepts, demonstrating the effectiveness of 3DL-aligned instruction in promoting deeper understanding.

The third application compared STEM students across nine different institutions using the same 3DL-aligned curriculum. This approach was aimed to capture the replication of the CLUE curriculum across different institutions. The team found the 3DL cluster set produced data shown in Figure 4 that highlights the consistency of the impact of the CLUE curriculum facilitating deep learning across institutions, regardless of whether the institution was private or public, large or small, or how it varied in student demographics. For all of these institutions, the General Chemistry 2 students in Figure 4 scored similarly, if not higher, than the Chemistry/Biochemistry graduating seniors shown in Figure 2.

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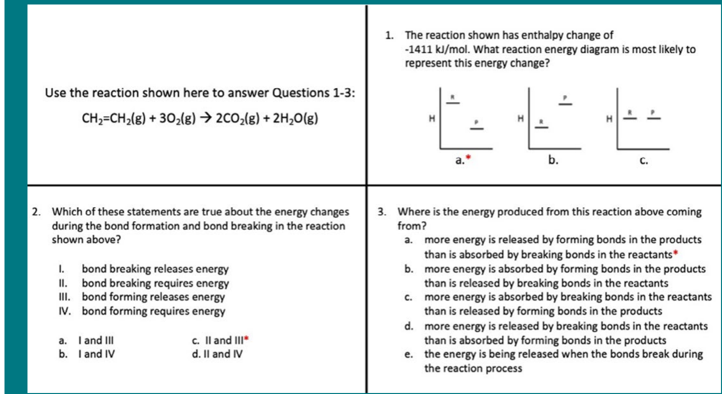

Figure 1: 3DL-aligned multiple-choice question set on thermochemical reactions.

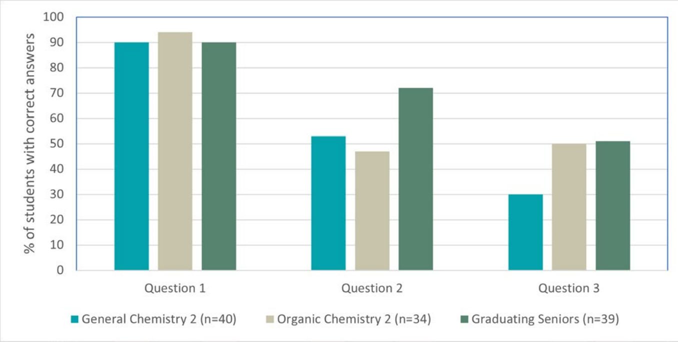

Figure 2: Results from 3DL multiple-choice cluster for Application 1 at Institution 1 for Chemistry Biochemistry majors at various time points.

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Impact on Students and Educators

The implementation of 3DL-aligned assessments and curricula has had a significant impact on both students and educators. The team suggests that more focus should be placed on ensuring students can correctly connect and apply the information they learn by aligning chemistry courses (content and assessment) with 3DL. Further, students should be encouraged and given the opportunity to connect ideas taught in their various chemistry courses throughout their undergraduate degree, which instructors can facilitate through incorporating 3DL-aligned clusters if restricted to only multiple-choice formatted questions.

3DL assessments and curricula provide students with a more engaging and meaningful learning experience. Instead of simply memorising facts, students are encouraged to think critically and apply their knowledge to solve problems. Students who have been exposed to a 3DL-aligned curriculum demonstrate a deeper understanding of chemistry concepts. They are better able to explain complex phenomena, make connections between different areas of science, and apply their knowledge in new contexts. This enhanced understanding is reflected in their performance on assessments, as well as their overall engagement and enthusiasm for the subject.

For educators, the 3DL clusters provide a valuable tool for assessing student understanding. These questions offer insights into how well students grasp core concepts and where they may be struggling. This information can help educators tailor their instruction to address gaps in understanding and provide targeted support to students. For example, in the applications presented above, evidence is shown for why one cannot assume students understand what is occurring with the energetic pieces of a reaction with respect to bond breaking and forming based on their ability to identify the correct reaction diagram. Therefore, students may be memorising the shapes of the diagrams without truly understanding them.

Dr Underwood's team also provides resources and training for educators to help them develop and implement their own 3DL-aligned questions. This support includes workshops, instructional materials, and ongoing collaborations with multiple institutions. By equipping educators with these tools, Dr Underwood and her team are helping to transform chemistry education on a broader scale.

Future Directions and Research

The success of the 3DL clusters has prompted Dr Underwood's team to explore new directions for their research. Dr Underwood is particularly interested in the long-term impact of 3DL-aligned education and how 3DL could be implemented in upper-division chemistry courses. She and her team are conducting longitudinal studies to track students' progress over time and assess the lasting effects of 3DL instruction. These studies will provide valuable insights into how well students retain and apply their knowledge as they advance through their academic and professional careers. Dr Underwood hopes to ensure that 3DL-aligned education can be implemented widely and effectively.

Despite the many benefits of 3DL-aligned assessments, there are also challenges and limitations to consider. One challenge is ensuring that these questions are appropriately demanding without being too complex or confusing for students. The team continually works to strike this balance, using feedback from pilot testing to refine and improve the questions.

Another limitation is the time and resources required to develop and implement 3DL-aligned questions. Dr Underwood's team is addressing this by providing resources and training for educators to assist with modifying existing curricular materials to align with 3DL. By overcoming these challenges, they aim to make 3DL-aligned assessments more accessible and practical for educators at all levels.

Innovations in Education

Dr Sonia Underwood and her team are at the forefront of educational innovation in chemistry. Their work on how 3DL-aligned multiple-choice questions can be used for a variety of purposes represents a significant step forward in promoting deeper understanding and engagement in chemistry education. By integrating core ideas, scientific practices, and crosscutting concepts, they are helping students develop the critical thinking skills necessary for success in science.

The impact of this work extends beyond chemistry, with the potential to transform education in other STEM fields. Dr Underwood's team continues to refine and expand their methods to pave the way for a new era of science education that prioritises deep learning and meaningful engagement. Through their dedication and innovation, they are helping to prepare the next generation of scientists for the challenges and opportunities of the future.

Dr Underwood's vision and leadership have been instrumental in driving this transformation. Her commitment to improving education and her innovative approach to assessments have inspired countless educators and students. As her work continues to evolve, it promises to make a lasting impact on the field of chemistry education and beyond.

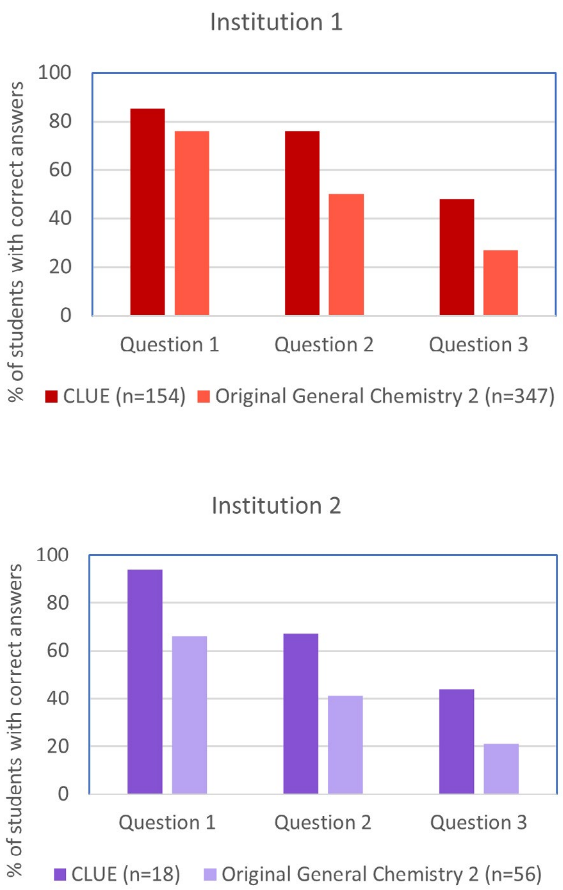

Figure 3: Results from 3DL multiple-choice cluster for Application 2 for STEM majors in General Chemistry 2 at two institutions using the CLUE.

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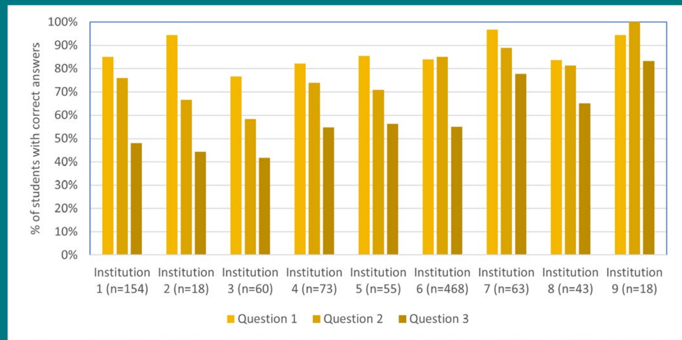

Figure 4: Results from 3DL multiple-choice cluster for Application 3 in General Chemistry 2 at nine institutions using CLUE curriculum.

MEET THE RESEARCHERS

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Dr Sonia Underwood is an Associate Professor at Florida International University, where she works in the Department of Chemistry & Biochemistry and the STEM Transformation Institute. She earned her PhD in Chemistry from Clemson University and completed a postdoctoral fellowship there as well. Dr Underwood's research focuses on integrating Three-Dimensional Learning (3DL) in chemistry education, aiming to improve students' understanding of core chemistry concepts and scientific practices. Her work has been widely recognised, and she has received several awards, including the FIU Top Scholar Award for Dedicated Mentoring in 2022. Dr Underwood has published numerous articles in reputable journals and is actively involved in various professional societies and educational initiatives.

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Dr Alexandria Roach recently earned her PhD in Chemistry from Florida International University. She completed her Bachelor of Science in Chemistry with a specialisation in Biochemistry at Barry University. In 2021, Dr Roach was awarded the National Science Foundation's Graduate Research Fellowship, which supports and recognises outstanding graduate students in select STEM disciplines. Dr Roach's dissertation research focused on student understanding, student perceptions and faculty perceptions of core chemistry ideas. Dr Roach is currently a high school chemistry teacher, where she's passionate about inspiring the next generation.

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KEY COLLABORATORS

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FURTHER READING

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