Mechanistic Explanations Across Undergraduate Chemistry and Biology Courses

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Abstract: Disciplinary silos and large amounts of specialized information in chemistry and biology courses undermines how students can make sense of these disciplines. This manuscript reports on how mechanistic reasoning across undergraduate courses may guide students towards more enduring and meaningful science learning. This team of chemistry, biology, and education researchers engaged in conversation about core mechanisms important for student learning in each disciplinary area that would connect to core mechanisms in the other disciplinary areas. The team also engaged in design work around written mechanistic explanations assessment items in each area. Those discussions prompted awareness of disciplinary and pedagogical similarities and differences about mechanisms. Our findings report on the mechanistic reasoning we focused on in each disciplinary area and how those were embodied in the assessment prompts. We discuss implications for teaching students who are traversing different subject matter information and ways of knowing.

Keywords: Mechanistic Explanation, Mechanistic Reasoning, Undergraduate Chemistry Education, Undergraduate Biology Education

Piecemeal approaches in undergraduate chemistry and biology education

Disciplinary silos and specialized ways of approaching problems within scientific fields such as chemistry and biology causes a piece-meal approach to education and information overload for learners. The result is often that students retain few ideas from information-laden courses that they reference in their later lives. Our team has been working to find essential aspects of science that can guide students through the information overload and towards more enduring and meaningful learning such as scientific mechanisms. Mechanisms of phenomena, or mechanistic explanation involves appealing to underlying factors, how those factors behave, and how the cause and effect chains give rise to the phenomenon (e.g., Krist, Schwarz, & Reiser, 2019; Russ et al., 2008, van Mil et al., 2016). Mechanisms have explanatory and predictive power and are highly generative for related phenomena (e.g., Bechtel & Abrahamsen, 2005). Emphasizing mechanism and mechanistic explanations may provide a promising way to focus students on powerful models, critical information, and ways of thinking that can help students make sense of phenomena inside and across disciplinary content areas.

In taking this approach, we have investigated how college students develop mechanistic explanations of key phenomena in introductory college chemistry, molecular cell biology, and organismal biology - a typical course sequence for many health-related majors. Our goal is to better understand how students are generating mechanistic explanations in these different contexts, what those look like, and eventually if students can recognize and build on the mechanisms from previous courses in future science courses. We want to test our hypothesis that focusing on mechanistic explanations across disciplines may be promising for enduring and meaningful science learning. To begin addressing this idea, we proposed the following questions, **"(a) what are some essential mechanisms and mechanistic explanations that can be leveraged across introductory chemistry and biology classes, and (b) how can those mechanisms be captured in written assessments to determine how students are understanding and using these core mechanisms?"** In this paper, we share our work identifying and comparing core mechanisms in chemistry and biology. We describe how we operationalized these mechanisms into written assessments to determine how students may be taking up these mechanisms and use this collaborative effort to point to potential barriers and opportunities in supporting student learning across disciplinary areas.

Theoretical approach

Our theoretical approach leverages prior research on mechanisms, mechanistic reasoning, and mechanistic explanations in science education (Becker et al., 2016; Russ et al., 2008; Southard et al., 2017; Talanquer, 2018). While there are several useful frameworks, we primarily leveraged our previously developed and tested mechanistic reasoning framework for written assessments across science disciplines (Krist, Schwarz, & Reiser, 2019) that includes (1) thinking at a scalar level below the phenomena, (2) identifying relevant factors that give rise to the mechanism, (3) unpacking the behavior of the relevant factors and (4) sequencing those relevant factors together to explain the behavior of the phenomenon. We recognize that not all systems can or should be described in cause and effect terms - that systems approaches are useful. Further we do not imply that all mechanisms are unidirectional (e.g., stochastic processes). At the same time, we think it is important that learners take forth some key causal mechanisms because they are extremely powerful for predicting and explaining phenomena in our lives. In combination with this framework, we leveraged expertise in chemistry and biology and research in reform-based undergraduate science education (e.g., Cooper & Klymkowsky, 2013) to choose focal mechanisms for undergraduate chemistry and biology students.

Methodological approach

Our research group is comprised of discipline-based education researchers in chemistry and biology and K-12 science education. Several members of the team have expertise in mechanistic reasoning and explanations. To address our research questions, we first chose a core mechanism and phenomenon in each disciplinary area that is important for students to know and would connect to mechanisms in other disciplinary areas. We began with protein structure and function in the molecular cell biology class and determined related core chemical processes in scalar levels below (for chemistry) as well as core biological processes at scalar levels above (for organismal biology). For example, how proteins are produced and how they interact with other molecules in cells can be explained by the electron distribution within molecules and the resulting forces between molecules. Protein structure and function can also predict why mutated proteins provide different biological functions for organisms which affects how organisms reproduce and evolve. We then leveraged Krist et al.'s (2019) framework for designing assessment items. In discussing the design of the assessment items, we found similarities and differences in our ideas about mechanistic reasoning. We co-constructed items that addressed mechanisms with mutually agreed-on importance.

Findings

Our findings report (a) mechanisms and mechanistic explanations across chemistry, molecular and cellular biology, and organismal biology courses and(b) how we embodied those mechanisms in written assessment items.

Mechanisms in introductory chemistry

In our introductory chemistry courses, students learn about how atoms and molecules respond and react to one another in systems over time. One important aspect of predicting how reactions will occur is to understand electron distributions and how this affects the interactions between atoms and molecules. While knowing how electrons move among atoms during interactions counts as a mechanism because it moves down one scalar level (from atom/molecule to atomic structure or electron), unpacks what that electrons do, and ties that back to the phenomena itself (the outcome of the reaction), it does not include a causal mechanism for why the electrons move or interact. A causal mechanism unpacks the properties of the electrons (they are negatively charged) to address the cause (attraction between oppositely charged entities) and ties those back to the outcome of the reaction. Knowing more about the distribution of electrons in a molecule and the electrostatic interactions that govern their behavior is powerfully predictive and makes learning chemistry more straightforward compared to memorizing multiple rules and combinations that when forgotten cannot be applied.

We hypothesize that learning how electron distributions can impact electrostatic interactions between and within molecules and atoms in chemistry can provide an underlying foundation for knowing more about biochemistry and other biological systems. While some fields including biology consider emergent complex systems (e.g., ecosystem interactions) which may not have a causal mechanism, changes in chemical systems are primarily thought of as having causes even if those processes are reversible. There may be multiple causes for interactions and some randomness in a system (e.g., random motion) that make a system difficult to predict. However, there are relatively few causal mechanisms, many of which can productively be explained at least in large part by aspects such as electrostatics. As such, causal mechanisms are an important part of understanding chemical reactions.

We have been tracing undergraduate students' ideas about causal mechanisms in introductory chemistry classes by asking a series of questions about the binding of a magnesium ion to a protein. First, we present a simplified version of two different protein binding pockets with the atoms of the amino acid side chains shown.

We then ask them to draw the magnesium ion in the pocket it would more strongly bind to. After they have drawn the magnesium ion, we asked students to explain why the binding pocket they chose better binds magnesium and to explain what causes the magnesium to bind to the pocket. In our analysis of students' responses, we are determining if they seem to understand the electrostatic interactions of the system (the unpacking of the factors involved in the mechanisms) and whether they can apply it to other contexts.

Mechanisms in molecular and cell biology

In molecular and cell biology, how proteins do their work and why a specific protein's structure causes a particular function lies at the core of almost all cellular functioning. Understanding critical ideas about how proteins work is powerful for predicting and explaining other phenomena. For example, explaining how cells move and coordinate with each other or how they generate and receive signals requires understanding of protein functions. These functions of protein lead to more phenomena, for example, neuronal processing, which can lead to complex behaviors, for example predator avoidance. Because proteins are the molecular machines that carry out the vast majority of cellular processes, understanding the mechanism by which proteins function is a powerful tool for explaining and predicting a wide range of biological phenomena.

The primary mechanisms of protein functioning that we targeted is how a protein binds with a ligand. The way a protein binds is related to amino acid's three-dimensional arrangement in the binding site as well as their properties such as polarity, hydrophobicity, acidity. These properties can be explained by electron distributions within amino acids that cause interactions between molecules and lead to binding specificity. In order to determine how undergraduate biology students understand ideas about causal mechanisms in introductory molecular biology classes we asked students to construct diagrams and provided written explanations of why two proteins have different functions. For example, students are given a representation of a hypothetical hormone that includes some molecular structure and ask to explain why genes cause one protein to bind magnesium ions while another protein binds to the hormone. In this way, we are able to determine whether students leverage mechanistic reasons – identifying amino acids as important factors a scalar level below, unpacking their properties and the resulting interactions, and linking this back to binding specificity and protein function.

Mechanisms in organismal and ecological biology

Finally, we have been working to understand the role of causal mechanisms in the organismal and ecological biology class. One of the main goals in ecology, for example, is to understand the causal and quantitative components in a system to accurately predict the consequences of perturbations. In many cases, the 'how' questions (how do things change, how much do they change and how are these changes caused) are more relevant than asking 'why' questions (why do things change) because the mechanisms for change can be multifaceted and complex (cascading events at multiple levels) or random (such as mutations). Much of ecology requires analysis of systems that are significantly more complex than the relatively simple systems considered on chemistry. One critical question to ask about mechanisms in such complex systems is at what scalar level does one need to 'go down' to generate an accurate and powerful yet simultaneously mechanistic explanation of these ecological and organismal systems? How might mechanisms be relevant in complex systems, does breaking down a system to a mechanism reduce its complexity too much, or does it introduce irrelevant complexity?

Even in complex systems, there are some fundamental causal mechanisms for students to understand. We targeted the mechanism of mutation that gives rise to variation in genotypes and consequently in phenotypes. Then we targeted how different phenotypes affect how different populations reproduce and interact in a community. To determine whether students can generate mechanistic explanations in these areas, we designed an assessment item that asks them how phenotypic variation arises in populations and why variation can cause changes in population structure. In this case, students must identify the factors several scalar levels below (differences in DNA due to mutation), and unpack processes (production of different proteins due to transcription/translation) which leads to differential functioning of the organism.

Conclusions and implications

We found differences and similarities in our discussions of what counts as a mechanism across the undergraduate chemistry and biology classes. For example, we had different ideas of mechanism regarding the role of causality, and how those can be elicited or embodied in the everyday words we use with students such as 'how' and 'why.' Additionally, what counts as mechanistic and causal for molecular and cellular biology (e.g., hydrogen bonding as a cause for protein binding specificity) may not count as causal in chemistry (e.g., electron distribution as a cause for hydrogen bonding). In other words, what one discipline views as either the phenomenon or the cause of the phenomenon and devoid of mechanism is viewed by another discipline as an essential part of the mechanism for a phenomenon at a larger scalar level. Further, while mechanisms in chemistry can sometimes be more easily narrowed to a few direct causal mechanisms than organismal biology, each disciplinary area aims to understand parts of the system and how they work together for determining causes and mechanisms as well as predicting future behavior.

Such findings point to potential challenges and opportunities for students. What counts as a mechanistic explanation to the appropriate level of depth and how that is described in everyday language varies across disciplines. This can be confusing for students if instruction doesn't help them navigate the different scalar levels and set expectations for acceptable mechanisms. At the same time, mechanisms as a whole can play an important role across content areas, bringing together ideas for future application. Some scaffolding such as using a common framework or language for identifying and generating causal mechanistic explanation may be useful for linking these ways of knowing across disciplines. Further, students may benefit from some just-in-time ideas comparing and contrasting mechanistic explanations across contexts and courses. We are still working to understand how students are engaging in these written assessments to determine what resources students see as relevant to a causal mechanistic explanation and what they leverage across disciplinary areas. Such work will inform efforts to improve undergraduate science education.

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