“Systems thinking encourages a safe space to offer different perspectives and insights”: Student perspectives and experiences with ST activities

Alisha R. Szozda[1], Zahra Lalani[1], Samira Behroozi[1], Peter G. Mahaffy[2], and Alison B. Flynn[1]*

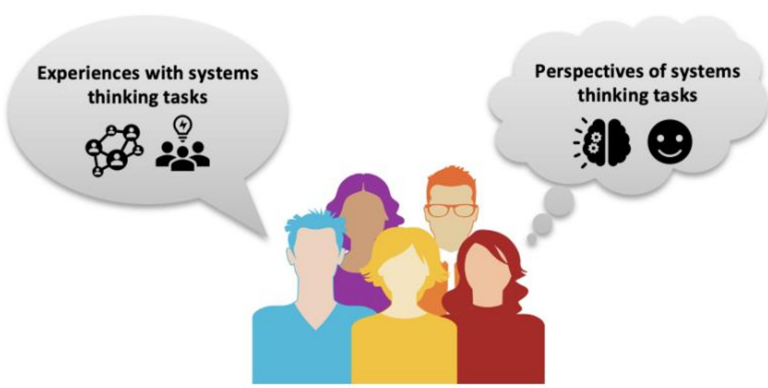
[1] Department of Chemistry and Biomolecular Sciences, 10 Marie Curie Pvt, Faculty of Science, University of Ottawa, Ottawa, Ontario, K1N 9A7, Canada

[2] Department of Chemistry and the King’s Centre for Visualization in Science, The King’s University, Edmonton, Alberta, T6B 2H3, Canada

ABSTRACT

Researchers and educators have been exploring systems thinking (ST) in chemistry education to better equip citizens for 21st century challenges; however, little is known about students’ perspectives and experiences. In this study, we investigated students’ perspectives of ST and their experiences with ST activities. We designed and implemented a ST intervention, performed individually and collaboratively, as well as follow up interviews. Twenty-four undergraduate and graduate students participated in this study and reported a variety of experiences and perspectives. For students’ experiences, we found that: (1) while collaborating, participants recognized and appreciated different perspectives, (2) participants included chemistry concepts and connections in their system maps despite having difficulties, (3) system maps emphasized problems/solutions and causes/effects and differed in terms of organization and intended purpose, and (4) limitations to system map construction included time, knowledge, and technology skills. Students also expressed positive perspectives of a ST approach based on their experience engaging with the ST intervention and believed a ST approach (1) is beneficial to learning, (2) captures interest and engagement, (3) allows perspectives to be shared and gained, and (4) provides personal, social, and professional relevance. Based on these findings, we suggest aspects to consider when planning and implementing ST activities and identify future research required to better understand the impacts of ST in chemistry education.

GRAPHICAL ABSTRACT



KEYWORDS

Systems Thinking, Qualitative analysis, Chemistry Education Research, Diversity and Inclusion, Undergraduate, Graduate

INTRODUCTION

Recent efforts have been directed toward understanding educators’ perspectives of systems thinking (ST) in chemistry education;[1–3] however, students’ perspectives are much less well known. While many ST resources and activities have been published, the extent of understanding student perspectives has been limited to receiving feedback of their experience.[4–6] Motivation and engagement in learning has been shown to play a role in academic outcomes therefore, students’ experiences (doing ST) and perspectives (thinking about ST) need to be better understood.[7] Gathering evidence of students’ experiences and perspectives with ST can contribute to best practices for implementing ST and its impact for chemistry education.

Current limitations in the educational system

Traditional teaching methods in chemistry typically place emphasis on compartmentalizing fundamental topics to get at the depth of chemistry knowledge and often pay less attention to knowledge and skills to make connections to other disciplines and global issues (Figure 1).[8] For example, a student learning chemistry through traditional approaches may learn specific properties related to chemicals but may struggle with identifying and understanding the impact chemistry has on global contexts and vice versa. ST has been proposed to compliment current teaching approaches to chemistry education that could aid in the development and transfer of knowledge and skills especially in introductory chemistry courses. Understanding complex challenges, such as those prioritized with the United Nations' Sustainable Development Goals (SDGs),[9,10] requires a systems lens. If a student is taught using a ST approach, this student will still learn the fundamental chemistry concepts but will develop additional skills such as: asking questions related to how a chemical concept or process may contribute to a UN SDG or identifying the intended and unintended consequences of the chemical.[8,11–14]

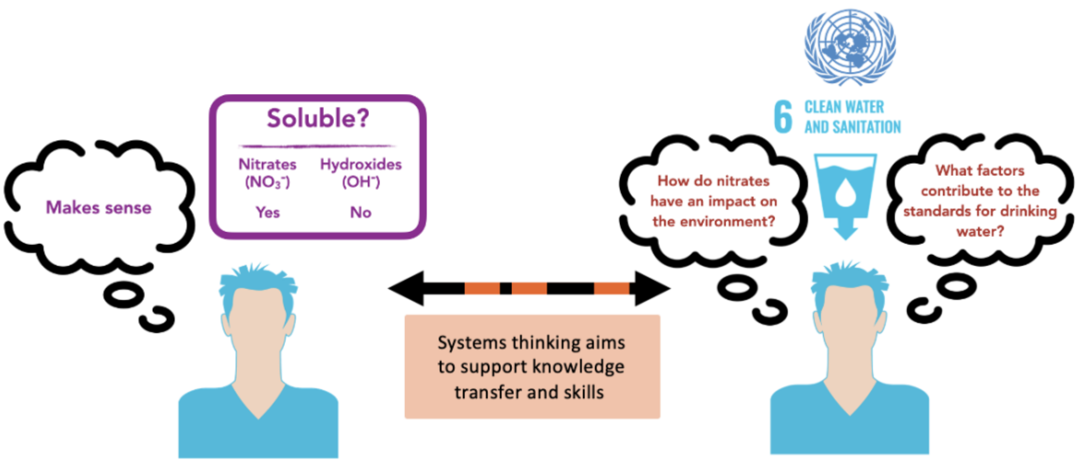


Figure 1. Difference between traditional teaching approaches and systems thinking approaches with supporting knowledge transfer and skills in chemistry classrooms. Left side: A student learning through a traditional teaching approach understands specific properties related to chemicals (e.g., nitrates and hydroxides). Right side: A student learning through a ST approach will identify the impact chemicals have on the environment and understand the factors involved.

Educational systems face challenges of preparing students for jobs that do not yet exist,[15] in which skills of adaptability, complex thinking, and problem solving are in high demand.[16] While universities around the world aim to equip chemistry graduates with the competencies and content knowledge required to be successful in their future careers, students have not fully developed professional skills (*e.g.,* collaboration skills, communication skills, leadership skills, learning skills, scientific thinking skills etc.) that are required by employers.[17–19] Building the capacity to understand and achieve the SDGs and expectations of a 21st century workplace requires evidence-based approaches to postsecondary STEM education.

The US National Research Council has identified collaboration and ST as skills required for jobs of the 21st century.[20,21] Providing opportunities for students to practice these skills and embrace the challenges will set them up for success in their future careers. There are distinct advantages that collaborative approaches have over individual problem solving. Collaboration allows information to be incorporated from multiple sources of knowledge, perspectives, and experiences, and provides opportunity to enhance creativity and quality of solutions stimulated by diverse group members.[22,23]

The proposed benefits of ST from other disciplines have propelled interest in implementing ST in chemistry education.[24–28] For consistency, we use the definitions of systems and ST that have been informally proposed by a working group of the IUPAC Systems Thinking in Chemistry for Sustainability: Towards 2030 and Beyond Project:[29]

Systems thinking is the ability to understand and interpret complex problems (ref [30], p 655). A *system* has at least three key characteristics: (1) components/parts, (2) interconnections between the components, and (3) a purpose [or function] (ref [31], p39). Systems exist at multiple scales, including microscopic, mesoscopic, and macroscopic, with the boundary conditions for a given system being established typically by its observer. A *systems thinking* perspective views a system as a whole and not just as a collection of parts. System thinking comprises both analytical and holistic thinking: identifying and examining system components, their organization, causal factors, and system boundaries (analytical), as well as describing and interpreting system level behaviors, and interactions of the system with its environment (holistic).[32–36]

Research suggests that developing ST abilities requires carefully designed instruction with focus on students' learning and applying ST skills.[32,37–41] There have been multiple lists of ST skills published in the literature,[1–3] including several studies in the context of chemistry education.[17,32] In our previous study, we used the five characteristics of systems thinking in chemistry education (STICE) to identify the baseline ST skills (skills demonstrated without explicit scaffolding) employed by undergraduate chemistry students.[42] This work helped us to understand what ST skills students do and do not readily demonstrate, so that educators can be informed on which ST skills to explicit scaffold in their instruction. In this current study, we aimed to further understand how to approach ST instruction for chemistry teaching and learning by investigating student experiences of and perspectives toward STICE activities¾ highlighting aspects of ST that may be beneficial and challenging for students.

Goals and Research Questions

This study is guided by the following research questions:

RQ1: What are undergraduate and graduate student **experiences** constructing system maps during **individual** and **collaborative** systems thinking tasks?

RQ2: What are undergraduate and graduate student **perspectives** of systems thinking tasks in chemistry education?

We aimed to achieve two goals in this study: (1) understand student experiences of and perspectives toward using a ST approach in individual and collaborative environments and (2) make explicit connections of our research findings to teaching practice. These goals can contribute to achieving long-term goals, such as identifying ways to best implement ST (including tools like system maps) into chemistry courses to support the development of ST skills.

METHODS

Context and Participants

We conducted this study with undergraduate science and chemistry graduate student participants at the University of Ottawa from Fall 2020 to Winter 2021, with ethics approval through the institution's Office of Research Ethics and Integrity (#H03-20-5585). We recruited undergraduate science students via course online platforms from any undergraduate chemistry course (taught in English only) in the Fall 2020 semester and chemistry graduate students via the Department of Chemistry and Biomolecular Sciences' email listserv.

The study sample for the ST intervention (N = 24) comprised eighteen undergraduate (U) and eight chemistry graduate (G) students. All participants had taken or enrolled in at least one university chemistry course and provided informed consent. Demographic data can be found in SI S1.1.

Data collection

We designed and implemented a ST intervention and interviews, previously described in this *Journal,*[42] to capture how students engage with three ST tasks related to climate change. We chose climate change as a topic because environmental and sustainability issues related to chemistry are authentic entry points to elicit prior knowledge and experiences. Authentic entry points refer to the opportunities that participants have to apply their knowledge to a task they will be actively involved in.

The intervention included (1) a pre-activity with cognitive and affective instruments, (2) three ST tasks, and (3) a post-activity with the same cognitive and affective instruments, a ST question and a demographic survey, all completed in one session, and online due to the COVID-19 pandemic (Figure 2). Details of the cognitive and affective instruments are provided in SI S1.2.

Figure 2. Design of the ST intervention and interviews used for this study.

Three tasks were designed to elicit ST skills, individually and collaboratively. In Task 1, participants individually created a visual representation (i.e., system map) on a climate change topic using an online collaborative whiteboard platform (Miro). In Task 2, participants engaged with an online interactive visualization tool (Design our Climate simulation)[43] with time to expand their original system map. In Task 3, participants shared their individual system maps in groups of two to three and combined them to form a new system map. The data included: (1) participants' written responses to questions on a google form for each task, (2) system maps from both individual and group tasks, and (3) participants' verbal explanations of their individual system maps in their groups, and subsequent discussion.

To investigate our RQ2 on student perspectives, we collected written responses to a ST question in the post-activity that asked participants how ST might affect their classmates' perspectives when engaging with ST tasks in a chemistry course.

Student Interviews

We developed a structured interview protocol based on the research questions and qualitative research methods literature (details in SI S4).[44,45] Interviews provided an in-depth understanding of how students interacted with each task in the intervention and their perspectives and reflections on the ST tasks. We invited all participants in the ST intervention to participate in follow-up interviews.

Of the 26 participants, four undergraduate and three graduate students participated in the follow-up interview. The interviewer asked students 15 questions that specifically related to the three tasks in the ST intervention (average of 30 minutes).

Group task protocol

When creating the ST intervention, we developed semi-structured group task prompts to elicit specific ST skills (goals from our previous study) and made these task prompts open-ended to promote conversation among the participants. Audio recordings from this group task (Task 3) served as a secondary data source that we used to compare to the interview analysis to capture student experiences and perspectives more broadly. Of the participants, 21 participated in the collaborative group task (17 undergrad and six graduate), resulting in ten groups (details in SI 1.2).

Data Analysis

We analyzed the data from the interviews, group task recordings, and post-activity responses using well-established methods (Figure 3).[46,47]

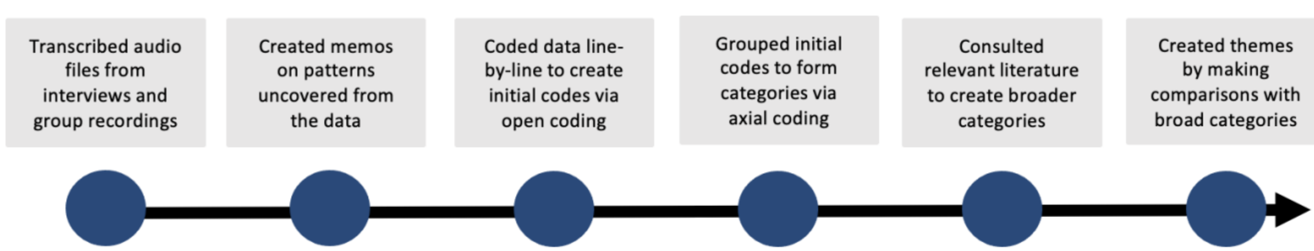


Figure 3. Overview of steps for qualitatively analyzing interview, group task recording, and ST question responses data.

First, we transcribed the audio files from the interviews and group recordings (Task 3) verbatim and wrote memos on patterns uncovered from the interview, group task, and post-activity ST question data. Next, we coded this data line-by-line via open coding to generate initial codes followed by grouping these initial codes to form smaller categories via axial coding. The researchers continued comparing the categories and consulted relevant literature to identify broader categories. Finally, we synthesized these broader categories similar in nature and derived themes based on the research questions. During data analysis, we created two coding schemes, one for student experience codes (RQ1), and another for student perspective codes (RQ2). The final coding schemes and a detailed explanation of the data analysis are presented in the SI S2 and S1.3, respectively.

Validity Evidence

We addressed the validity of our instrument and the findings using well-established methods including content validation, response process, triangulation, disconfirming evidence, peer debriefing, and providing a rich description of the participants' experiences and perspectives and the context of the study, as explained in the SI S1.5.[48–50]

Since this analysis aimed to explore and understand the social phenomena of people's experiences and perspectives of ST, we focused on maximizing validity and trustworthiness rather than objective reliability, such as inter-rater reliability. We were not interested in identifying the replicability of the results from our study as our focus was on exploring phenomena that had not previously been found. Our work contributes to exploring the unknown about ST, specifically, student perspectives and what it looks like for students to engage with ST in chemistry education.

Theoretical Frameworks

Two overarching constructivist learning frameworks guided our research: (1) modern information processing theory (IPT) and (2) sociocultural theory.[49]

IPT involves aspects related to the information people attend to, consciously or subconsciously, working memory, and how they encode and retrieve learned information. Once the information is transferred to the working memory encoded, the learner can (1) relate encoded information to knowledge in their memory, (2) store new knowledge in their memory, (3) and retrieve the information as needed (Figure 4).[42,51] Modern IPT incorporates learners' characteristics (e.g., self-regulation, beliefs, culture, and affect) and the learning environment as these factors greatly influence learning.[10,42,52]

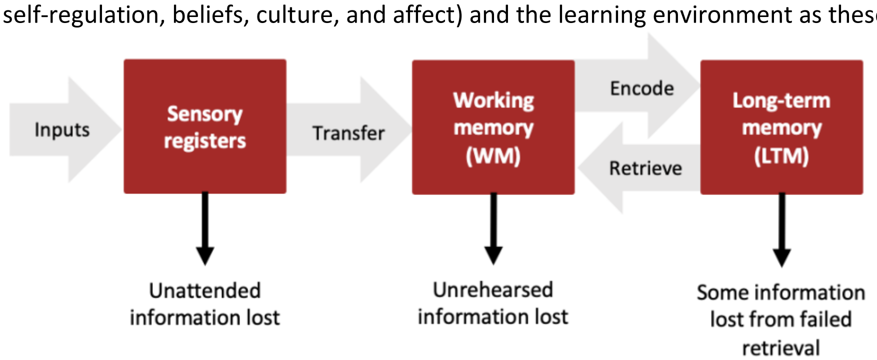


Figure 4. The model of modern information processing theory.

Researchers predict that educators can harness students' diverse range of prior knowledge in ST approaches beyond just chemistry knowledge.[53] Therefore, educators need to consider strategies for effectively activating learners' prior knowledge, including learners' experiences, beliefs, and non-content factors (e.g., attitude, cognitive expectations, motivation, self-concept, self-regulatory strategies, understanding the nature of science).[10,42,53]

Modern IPT guided our research as it explains how learners would likely use their prior knowledge in a particular learning environment (e.g., ST intervention) to determine what components of a topic will be embedded into their systems maps.[42] Relevant prior knowledge from the learner's long-term memory impacts how that knowledge is stored and organized.[54] In this study, students constructed individual system maps based on a topic they chose on climate change, which allowed them to retrieve prior knowledge from their long-term memories that could appear interesting, informative, or culturally relevant to them.[53] Each student presented this knowledge as a two-dimensional representation (i.e., system map) and created verbal explanations of the knowledge network within each of their minds.[55] When new information is presented (e.g., from other learners or learning tools), students may perceive this new information, use it in their working memory and integrate it within their existing knowledge structures. As this study explored student experiences constructing system maps on climate change, we were interested in what information students retrieved from their long-term memories and how they organized this information when constructing their system maps. Using IPT to interpret these findings can lead to implications for teaching and using system maps in a ST activity. More information about how this theory is embedded into the three ST tasks of the ST intervention can be found in the SI S1.4.

Sociocultural theory explains how the learning environment plays an integral role in cognition.[53,56] This theory stresses the importance of culture and social interaction in developing and shaping individuals, with an essential application being peer collaboration.[56–58]

Researchers have previously proposed that ST can be used to engage students in social, historical, and cultural interactions.[53] Since chemistry classrooms are composed of students from diverse backgrounds and experiences, these students can share and gain different ideas and perspectives, offering rich opportunities for them to learn from one another. If a student achieves a different self-awareness or perspective from engaging in ST activities, their transformed thinking can be explained by sociocultural theory.[53] In the design of this study, we explicitly created a collaborative ST task to investigate how student interactions influence the construction of system maps and whether new perspectives are shared and gained. Student experiences and perspectives can shed light on the potential for a ST approach to increase diversity and inclusion when learning chemistry.

The following sections describe the key themes uncovered from the analyses.

RESULTS AND DISCUSSION

RQ1: What are undergraduate and graduate student experiences constructing system maps during individual and collaborative systems thinking tasks?

The 26 participants had varying experiences related to constructing system maps individually and collaboratively. Here, we describe these student experiences in more detail based on the themes uncovered.

While collaborating, participants recognized and appreciated different perspectives.

Most participants described having beneficial experiences when constructing system maps collaboratively, with a few challenges.

Participants recognized and appreciated different perspectives and ideas from group members. Participants indicated they gained new perspectives or ideas related to the ST task from their group member(s) because having a group discussion allowed them to bounce ideas off each other and consider new ideas they did not think of initially. Some participants mentioned that the group system map combined all ideas from group members since people have different ways of thinking about a topic. These responses typically come from students' explanations of why they found the group system map better than their individual system map. Participants also appreciated sharing perspectives and ideas with others because they found thinking about these different perspectives helpful and interesting (Figure 5).

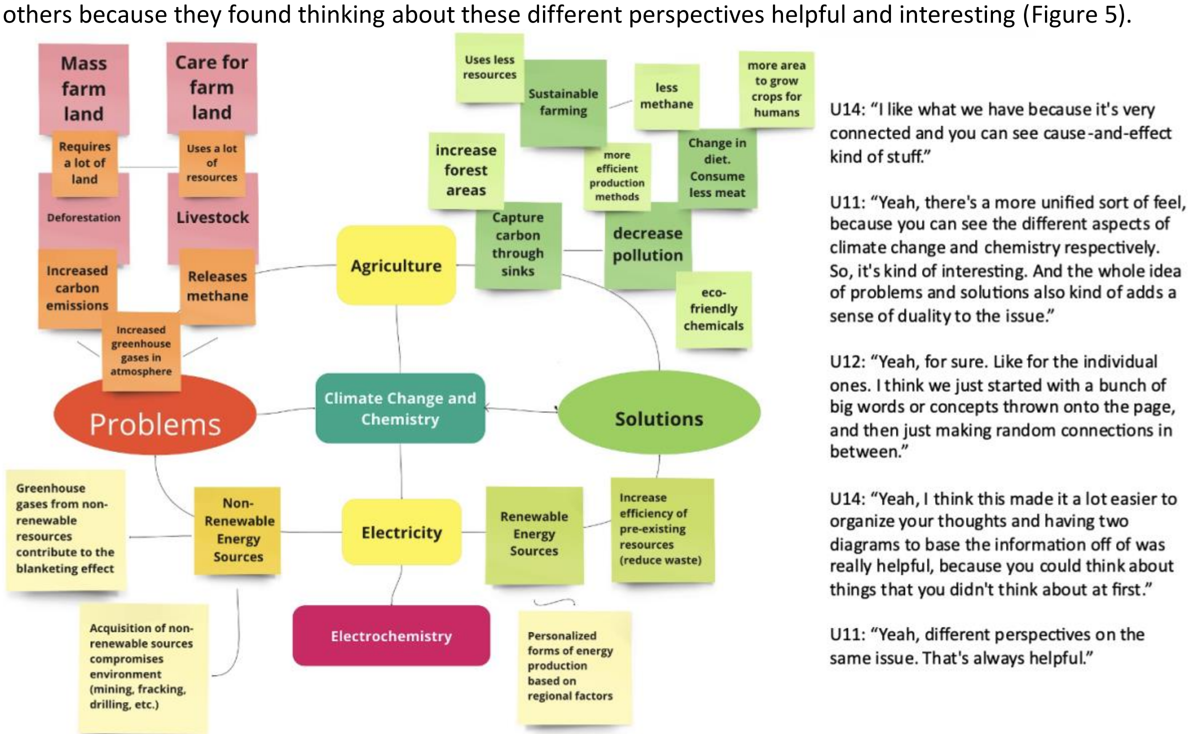


Figure 5. Conversation among three undergraduate students in the group task.

In the collaborative ST activities, students had the opportunity to share different perspectives that they appreciated when connecting chemistry to climate change. These findings demonstrate the potential impact that collaborative ST tasks could have on students' learning and engagement. ST could provide a particular opportunity to invite and share diverse perspectives, including students' lived experiences and prior knowledge. These opportunities could allow students to connect to chemistry concepts from a wider variety of perspectives which is often not provided when chemistry is taught as siloed topics. Students' reflections in Figure 5 communicate why it is important for educators to embrace diversity into the chemistry classroom. Activities that allow students from diverse backgrounds to share their ideas and experiences with others can facilitate educational outcomes such as cultural knowledge and awareness, recognizing the complexity of issues, and learning to work with different kinds of people.[59,60] When students with diverse perspectives interact, they can bring more complex thoughts and challenge biases that are present in the course content and these interactions can support active thinking, cognitive sophistication, and intellectual engagement.[61–65] More research is needed to investigate if using a ST approach can produce these cognitive and affective outcomes.

Group system maps allowed students to bring more aspects together and give a more well-rounded view of their topic. During the interviews, some participants explained that they liked the group system map more than their individual one because combining ideas brought certain aspects together to give a more well-rounded view. G4 mentioned how their challenges with learning chemistry and biology come from needing explanations in each discipline. When merging their system map with their partners, they gained an additional perspective that helped bridge connections between biology and chemistry concepts (Figure 6).

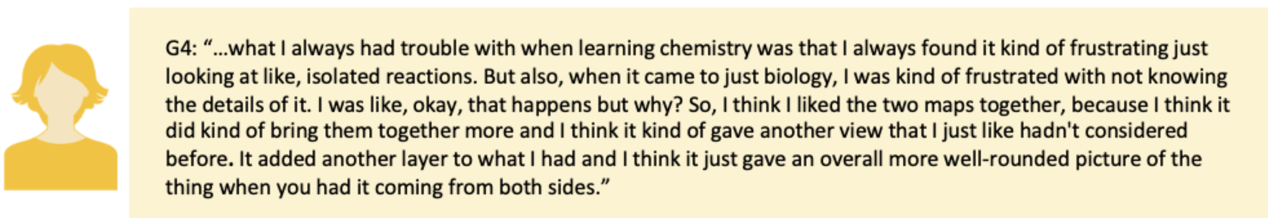


Figure 6. G4 quote.

G4's quote describes the value of bringing together knowledge from multiple disciplines. G4 appreciated being guided to think more deeply about the chemistry connections and consider multiple aspects of their topic. Similar findings have been shown on students' perceptions of using system maps to visualize chemistry.[66] When engaging in systems mapping exercises, students valued the opportunity to reflect on multiple aspects of chemical processes.[66] These findings suggest that a ST approach has the potential to contribute to cognitive learning outcomes, especially when students are given the opportunity to explore different perspectives.

Constructing group system maps was more meaningful than individual maps. Sharing perspectives and ideas with others also led to participants creating more meaningful system maps. Some participants thought the group system map was better because it contained more "meaningful concepts" or created a product that matters (Figure 7).

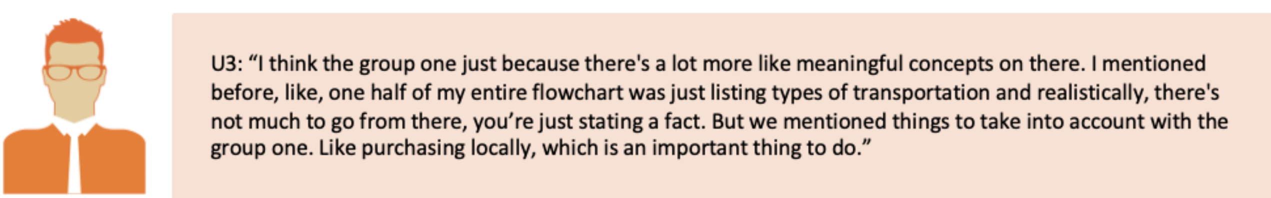


Figure 7. U3 quote.

Other participants mentioned that combining system maps in a group provided opportunities to discuss solutions to make an impact or allowed them to take away a more significant message about how to make a change to address a problem (e.g., climate change) (Figure 8).

G2: "I guess that we see completely different aspects, but they are still correlated, like there are still linked. As you said, they're part of the system. You can't only consider one without considering the other because they both impact like the pollution or climate change on the planet. So, if you put all your efforts on one, the other side is still problematic. We have to be strategic on the effort we put in things. You can't put all your efforts in one thing. You have to find a way to compromise between all these aspects."

Figure 8. G2 quote.

The findings indicate that ST collaborative approaches could enhance students' learning and critical thinking when incorporating their group experiences and perspectives into the learning environment compared to individual tasks. Thinking critically as a group could lead to a product (e.g., system maps) that is more meaningful to students which may increase overall engagement with learning chemistry. Providing opportunities for students to engage in discussions with individuals who have different perspectives can lead to improved educational outcomes and serve as a catalyst for new ideas.[61,67–70]

Collaboration helped students elicit systems thinking skills. Participants' ST skills were also enriched when having the opportunity to discuss ideas and share perspectives. Collaboration helped participants with the ST skill: **identifying additional concepts and making connections**. Some participants mentioned they would add more concepts to their individual system map based on the group task, or they found connections between different ideas or topics more easily in the group setting. For example, U12 stated that having the opportunity to discuss ideas in a group allowed them to find interconnections between different ideas more easily (Figure 9).

U12: "The main idea that connected all our visual representations is the fact that with our topics, there are associated problems that contribute to climate change, or maybe other environmental problems, and the fact that we learn of potential solutions to those problems from doing the simulation. So, once we did this, it made it easier to have main ideas on the problem side of the graph and then the solution side of the graph and then from there It made it easier to connect the topic of agriculture to electricity. … So, when we have the chance to discuss our visual representations, I think the great benefit of that is you can bounce off ideas much more easily when you're discussing with other people than when you're by yourself. And you can find interconnections and correlations between different ideas much more easily."

Figure 9. U12 quote.

Collaboration also helped participants with the ST skill: **identifying emergence**. To identify emergence, one must distinguish a property or behavior that result from interactions between two or more system's parts, rather than a property or behavior from an individual part (isolated from the system).[32,42] In this study, the group task helped participants identify a new topic or purpose for constructing their system map that emerged when considering similarities between their individual topics. Identifying a new topic led to some participants identifying a more significant meaning or importance for constructing their system map as previously shown (Figure 7). Six of the ten groups constructed their system maps from scratch, starting with a new topic from their conversation (**Error! Reference source not found.**A). The four remaining groups decided to copy one or both of their system maps, placed them side by side and tried making connections between the concepts (**Error! Reference source not found.**B). One of these groups brought up a topic that emerged from their group discussion, but this topic was not the starting point for constructing their system map (SI S3.2).

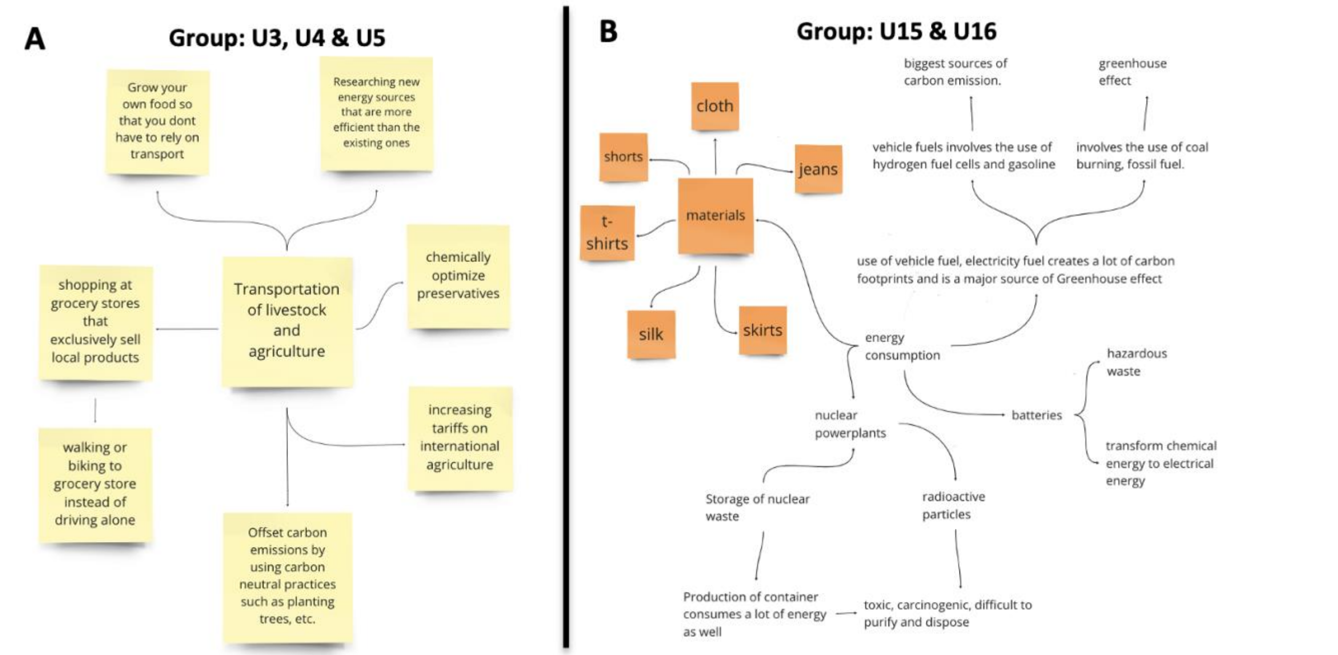


Figure 10. Examples of group system maps. A (left) represents a group system map constructed using a new, emergent topic. B (right) represents a group system map constructed by placing individual maps side by side and making a connection.

Participants may be able to identify new or emergent topics through discussions but may not know how to present the information in a visual representation. Drawing on IPT, participants may have fragmented or misconnected knowledge structures in their long-term memory, their knowledge was not appropriately activated, or their working memories were overloaded.[56,71,72]

Collaborative approaches have been found to provide social, psychological, academic and assessment benefit for students' learning and skill development.[73–75] Learning theories support that social and cultural interactions are critical for stimulating developmental processes, fostering cognitive growth, and transforming students' learning experiences.[56,57] We found collaboration to be beneficial for eliciting ST skills, unsurprisingly.

Most participants reported positive and beneficial experiences from collaboration; however, one participant identified a disadvantage of group maps and others described having challenging experiences when constructing system maps collaboratively.

U12 identified that when focusing on the big ideas in their group map, specific concepts can be excluded (U12, Figure 11). Group tasks allowed participants to focus on the bigger, overarching ideas related to their topic but at the expense of excluding more specific concepts from the group system map. Educators would need to explicitly scaffold and prompt students to think about finer granularity levels (e.g., molecular) related to the topic of interest.[76]

A few participants mentioned that having different ideas and topics as a group made it more challenging to make some connections (G1, Figure 11). One participant indicated that considering more perspectives and concepts from their partner can be overwhelming (G4, Figure 11).

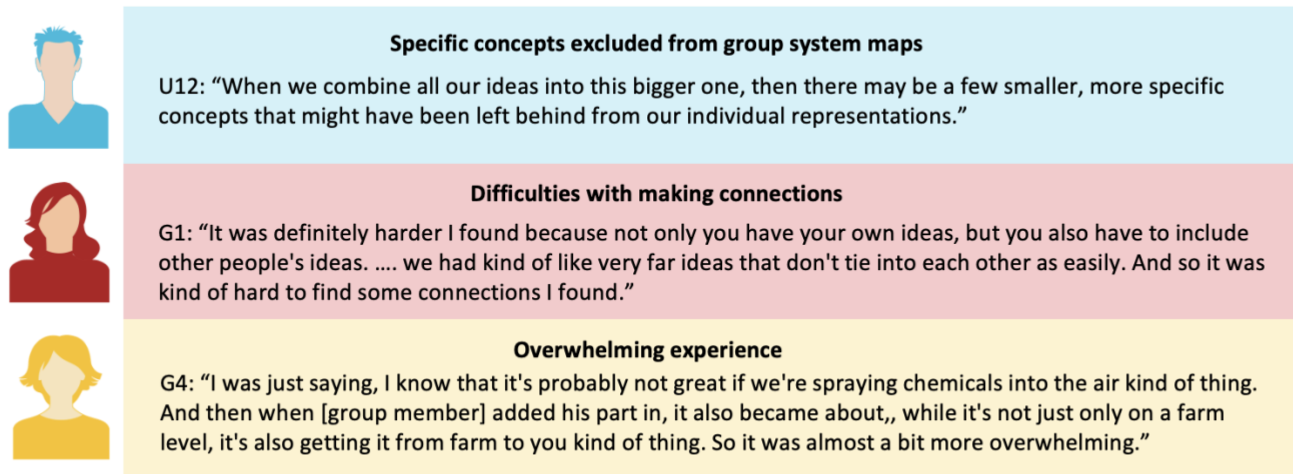


Figure 11. Examples of group map challenges and disadvantage reported by participants (U12, G1, and G4).

These student experiences highlight potential challenges that educators should be mindful of when integrating collaborative ST tasks in a course. To ease students' feelings of being overwhelmed, educators can consider how to incorporate new ideas and perspectives slowly, providing time for students to digest and sit with this new information. Perhaps, asynchronous ST opportunities can be implemented for students to work at their own pace. Educators should consider ways to include those who are neurodivergent (e.g., autistic, ADHD, dyslexia) as working in a group can be overwhelming and ineffective.[77] Equity, diversity, and inclusion (EDI) researchers have suggested that student-instructor interactions in an active learning environment can also promote students' success.[68] In particular, "demonstrating confidence in students' abilities and reinforcing a growth mindset will encourage students to persist through challenging activities" such as challenges with making connections.[68]

Overall, the findings presented in this theme suggests the value of ST approaches for improving EDI as well as decolonized and Indigenous perspectives in chemistry education, which has yet to be investigated. Collaborative ST tasks could connect chemistry and the learning environment with personal experience, interest, culture, and knowledge by engaging diverse students in conversations that are rarely encountered when traditional teaching approaches in chemistry education are used.[78] Inclusive teaching pedagogy that supports the experience of a diverse student population can enhance the learning and success of all students, support STEM innovation, decrease disparities in the academic success of underrepresented students, and increase student retention and persistence in STEM programs.[79–85] While our findings identified potential benefits of ST approaches, further investigation is needed to measure inclusion and equity outcomes of a collaborative ST approach in STEM education.

Participants made chemistry concepts and connections despite having difficulties.

Participants made connections to chemistry using different approaches. These approaches include incorporating general knowledge from personal experiences, adding concepts by using a ST lens (e.g., thinking about interconnections, inputs/outputs, causes/effects, problems/solutions, zooming in and out of different perspectives), and incorporating disciplinary knowledge (Figure 12).

Ideas from personal experiences and using a systems thinking lens	Includes disciplinary concepts considering chemistry's relevance
G1: "I focused on sustainable meat industry. So, a lot in the past, like right now. There is a big push for people to become vegetarians, vegan. And although it is possible, that is a great way to reduce greenhouse gas emissions, a lot of people have a hard time doing that because of either dietary restriction. And honestly just like culture. Coming from a Latino family, it is incredibly hard for people to be vegan because meat has been a staple of the diet. So maybe there is a land use and agriculture, that could focus on sustainable meat industry."	U10: "So that's when I introduced the chemical process, combustion being the breaking of bonds, therefore an exothermic process, and now the energy that is released from that exothermic process is what powers the vehicles. However, there are some byproducts from that combustion process that are gaseous in nature, and the gaseous byproducts are released into the atmosphere combining with air to form molecules that can degrade the ozone layer or capture heat."

Figure 12. Examples of approaches used to add concepts by participants (G1 and U10).

Despite these efforts, participants identified difficulties making chemistry connections or described only surface-level features of chemistry when integrating concepts into their system map. During the interviews, six of the seven participants demonstrated difficulty with making chemistry connections when asked to explain how a macroscopic concept in their system map connects to a molecular concept. Some participants mentioned molecular level concepts but described chemistry connections using descriptive features or did not explore the depth of these chemistry concepts in their maps. For example, U6 mentioned molecular concepts (e.g., carbon dioxide, methane, and nitrous oxide) when explaining their system map but they did not explain or show the sources of how the molecules are produced or how they increase the global temperature (Figure 13).

U6: "…And then there's public transport and carpooling, which can decrease the emission of CO_2, which is obviously better for the environment. And then the next one would be cars and vehicles. These cars and vehicles can emit greenhouse gas gases, such as CO_2, methane, and nitrogen oxide. And this would obviously increase the total global temperature as the atmosphere traps more heat, which raises the temperature, which is not good for the environment."

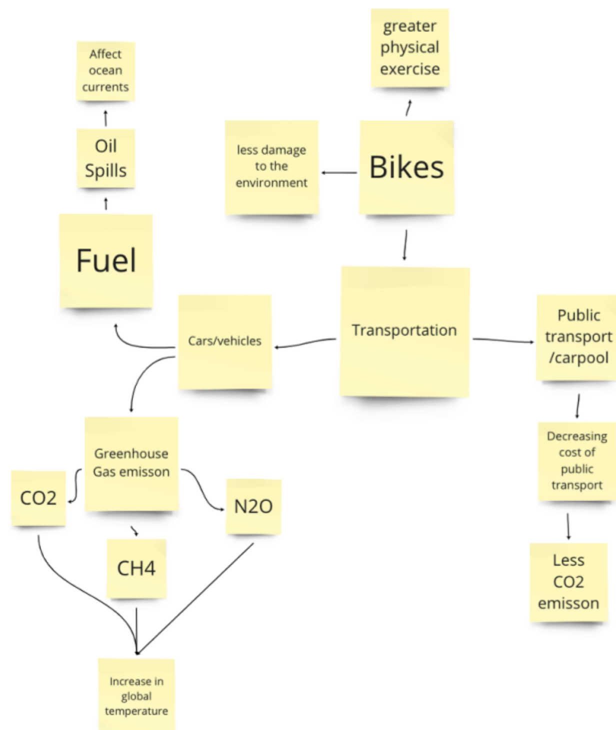


Figure 13. U6 quote.

These findings are not surprising considering our previous research shows that participants' system maps had substantially more concepts and connections at macroscopic levels of granularity than submicroscopic levels.[42] Other researchers have found that learners typically reason at the macroscopic level and have challenges meaningfully switching back and forth between these levels of representations.[86–91] Typically, chemistry teaching is focused on the submicroscopic level (via the representational level), which does not automatically help students move comfortably between all levels of representation.[92,93] As a result, students can get confused and lack of motivation towards chemistry.[88]

Participants also indicated they had difficulty or were uncertain about creating chemistry concepts and connections. One participant mentioned that they would like to have focused more on the chemistry aspects of their topic but lacked climate knowledge from news sources and education (Figure 14).

U12: "I would say doing this, I realized that I definitely could focus more on the chemistry aspects of climate change, because usually, I would hear about it from reading news stories or conversations with people in general, so we don't really get too into the finer scientific details of climate change. So at a school, kind of thinking more about the chemistry side of things like, thinking more of farming materials as chemicals, and the pollution and even thinking of the nutrients as chemicals, because for some reason, just because farming has been part of human life for so long, like fertilizers are chemicals, but it's seen as an everyday thing."

Figure 14. U12 quote.

Our findings show that participants may not have the opportunity to learn scientific details of climate change. Educators may teach chemistry concepts related to climate change, but it may not be taught meaningfully to the learner or the connections between chemistry and climate change are not made explicit. Therefore, participants included concepts in their system maps that predominately related to their personal experiences and what they obtained from news sources, which may or may not be accurate representations of climate science principles.

Traditional teaching approaches in chemistry often lead to students not being able to use or transfer their knowledge effectively in situations where it is needed, having difficulties with recalling what they are learning, and over-simplifying their understanding of complex phenomena.[94–97] Therefore, chemistry educators and professional associations have been advocating that chemistry curricula need to incorporate a ST approach so that students can understand connections between chemistry and its wider impacts to society, economy, the environment and human health.[8,12,102,108,109,110] When implementing a ST activity in a chemistry course, in the context of a specific global issue, the educator needs to (1) explicitly highlights the role that chemical concepts and processes play in the global issue and (2) provides opportunities for students to use, articulate, and demonstrate ST skills in new contexts.

System maps emphasized problems/solutions and causes/effects and differed in terms of organization and the intended purpose

Organization of system maps. Most participants constructed their individual and group system maps by adding causes/effects and problems/solutions that are aspects of ST skills and show promise for students' ST skill development. Of the participants who added causes/effects and problems/solutions, some participants organized their system maps starting with their main topic, creating branches to subtopics, and then adding ideas based on these subtopics (Figure 15a), while other participants only added ideas related to their main topic (no explicit branching into subtopics) (Figure 15b)

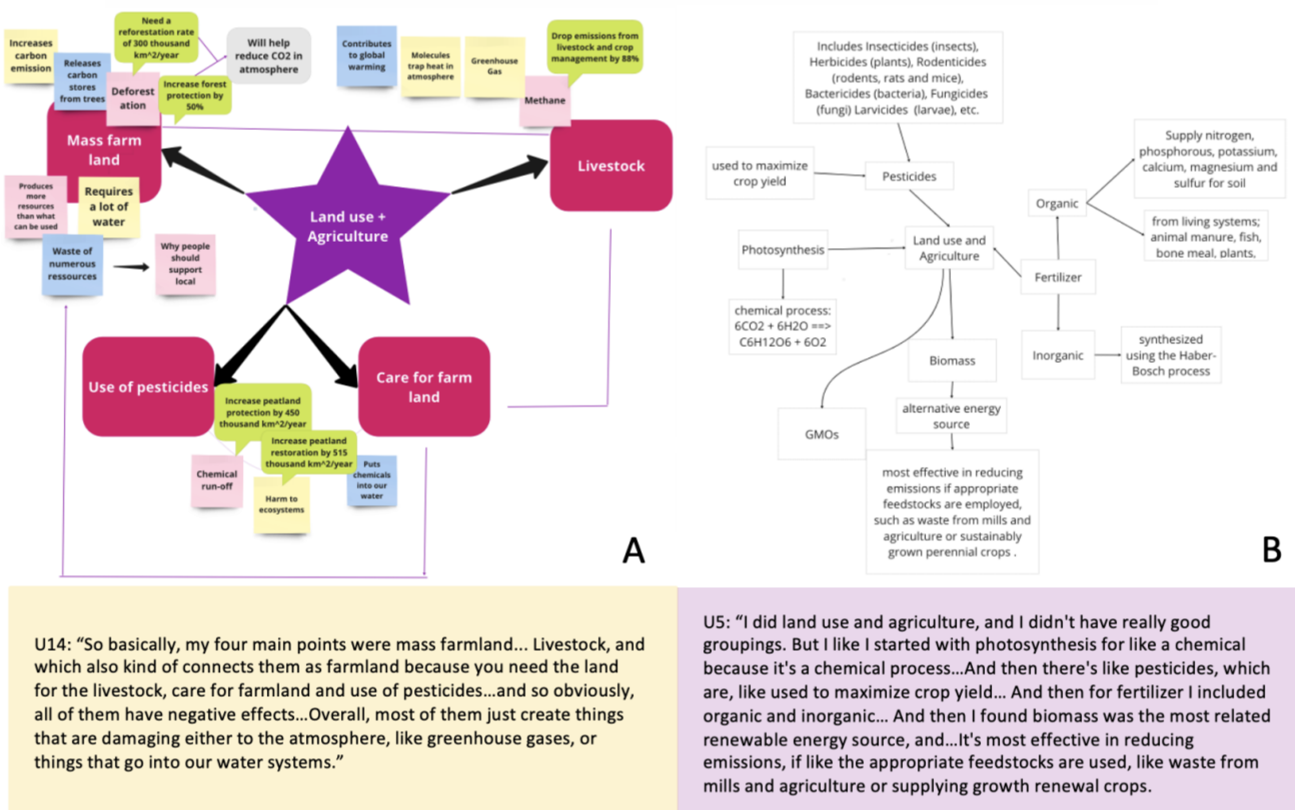


Figure 15. Example of individual system maps with different organizational strategies and participants' explanations of how they constructed their system maps. A represents U14's system map that is organized by starting with their main topic, creating branches to subtopics, and then adding ideas based on these subtopics. B represents U5's system map that is organized by starting with their main topic and then added ideas related to this topic (no explicit branching into subtopics).

We used IPT to interpret the differences in organizational strategies and the number of interconnections in participants' system maps. Generally, participants who organized their system map with subtopics made more interconnections compared to those who did not. Therefore, participants with well-organized knowledge of climate change may be more able to identify the relevant features of their topic and consolidate new information via chunking (i.e., grouping information). A well-organized knowledge structure could lead to more purposeful organization of their system maps (addition of subtopics) and the ability to identify interconnections among concepts more easily using this approach compared to participants with less organized prior knowledge.

These findings indicate a greater need to teach students how to approach system map construction when planning to use them in a ST activity. One potential approach that can be introduced to help students organize and visualize concepts and connections is using a System-Oriented Concept Map Extension (SOCME). SOCMEs group concepts into subsystems to define the system of focus and its boundaries and can help users to explicitly make connections between subsystems.[12] An online interactive tool called the SOCKit has been recently created to facilitate SOCME construction.[100] Overall, using a guided approach may lower students' cognitive load demands when learning about chemistry's connection to complex problems and they may be better positioned to make interconnections.

Intended purpose of construction. In some cases, participants' intended purpose of constructing their system map limited the number of concepts or connections they included in participants' system maps. Some participants intentionally wanted to keep their system maps simple by not including many details or expanding too much on other topics or issues. Other participants indicated they would refine their system maps for different audiences and would reconstruct or reorganize their system map to make it more presentable for others to view or for educational purposes (e.g., handing it in as an assignment and giving a presentation) (Figure 16).

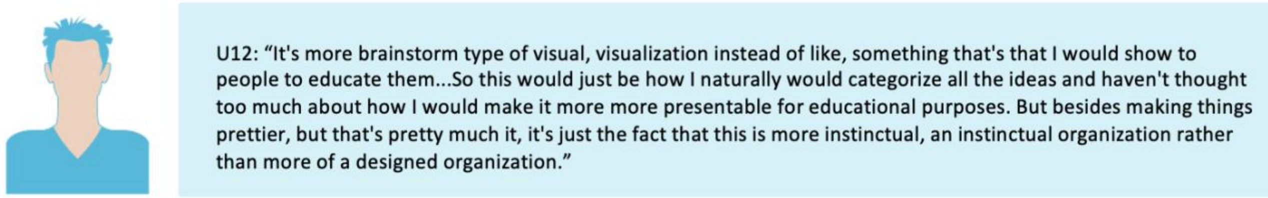


Figure 16. Undergraduate student 12 (U12) quote.

Complementing these findings, we found that participants explained more connections and concepts verbally compared to concepts and connections shown in their individual and group system maps (SI S3.2). Therefore, using both system maps and verbal explanations gave a better representation of participants' thinking. Based on our findings, one can imagine many educational purposes for ST (e.g., presentation, brainstorming for personal learning and navigating connections) and the need to make expectations and learning outcomes clear at the start of ST activities.

Limitations to system map construction included: Time, knowledge, and technology skills.

Participants reported that time, knowledge, and technology skills limited the construction of their individual and group system maps.

In line with our previous findings, limitations of participants' knowledge prevented the expansion of their system maps. During the interviews, some participants mentioned they stopped constructing their system map because they were unable to think about anything else to add. Other participants in the group task made comments about their uncertainty of making connections or adding concepts (U3, Figure 17).

We also found that system map construction takes more time than given for individual and collaborative tasks. Participants mentioned that they needed more time to add to their individual system map before and after engaging with the simulation. Additionally, some participants would have added (e.g., added more concepts and connections) or made changes (e.g., organized it better) to their system map if they had more time (U9, Figure 17). Time was also a factor for constructing group system maps, as some participants mentioned they would have liked to make more connections between topics, but there was a time constraint.

Lastly, participants reported problems with technology tools (e.g., Miro, computer) used in the ST tasks. From the interviews, one participant indicated they stopped working on their system map due to having problems with using the online whiteboard, Miro (e.g., Wi-Fi lagging connection). Other participants generally mentioned difficulties because they did not know how to use the software, even following a tutorial (G1, Figure 17).

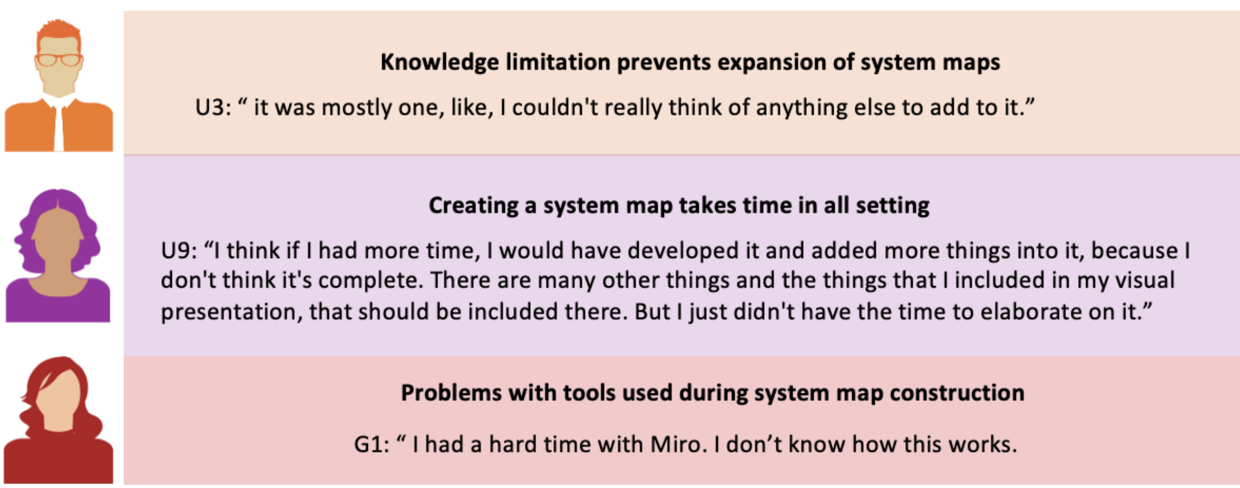


Figure 17. Examples of knowledge, time, and technology skill limitations reported by participants (U3, U9, and G1).

Overall, these findings suggest that students need time and space for deep thinking to engage in ST. However, time, knowledge, and technology skill limitations are not specific to a ST approach. Other studies investigating different learning approaches have found time constraints and technical issues were major factors preventing students from completing specific content modules or engaging at all with an intervention.[101,102,103] Literature suggests that learners with limited domain knowledge can struggle to deploy metacognitive strategies to determine what is relevant and generate questions for investigation, which can affect how learners' organize and present their knowledge.[94,104] Therefore, students need to develop adequate domain knowledge in class that they can integrate with their prior knowledge and experience. They also need explicit scaffolding and support to engage in these metacognitive skills so that they can transfer these skills to different contexts.[94] Providing additional scaffolding to support the use of online technologies and development of technology skills can also help alleviate technology-rated limitations in ST activities. Additionally, considering time and providing flexibility to complete ST activities or assessments will be important for engaging students in ST. Such changes will likely involve decisions about what current aspects of a given course can be removed (e.g., are of lower priority).

RQ2: What are undergraduate and graduate student perspectives of systems thinking tasks in chemistry education?

Students had varying positive perspectives about ST after engaging with the ST activities. Here, we describe four themes uncovered from our analysis based on (1) students' perspectives on their engagement with the ST tasks and (2) their perspectives of other students engaging with ST tasks in a chemistry course.

Systems thinking may be beneficial to learning.

Participants stated that ST can help other students to (1) understand how and why concepts are connected, (2) better understand chemistry and its application to the real world, (3) give a sense of purpose to learning chemistry and (4) allow students to engage in critical thinking.

Participants believed that ST could help students to better understand chemistry, the relationships between topics, and how and why one concept is connected to another. These findings were also elicited during participants' interviews. U12 mentioned that their overall experience with the ST activities was good because physically making the connections between the concepts was very help to them.

Some participants' responses stated that engaging with ST can allow students to relate real-life to chemistry concepts or teach students the many applications that chemistry has in the real world. One participant also mentioned that this approach may help students connect concepts in chemistry to other disciplines (Figure 18. G7 quote.Figure 18).

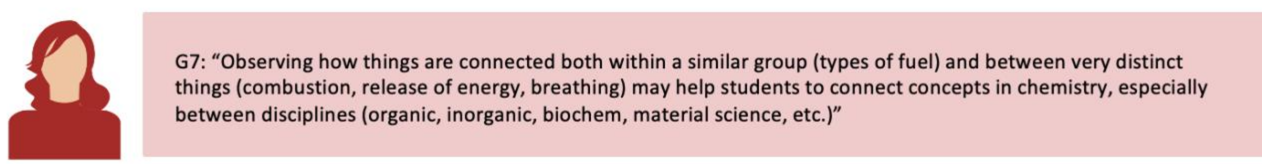


Figure 18. G7 quote.

These findings suggest that ST may provide the opportunity to connect chemistry more explicitly to real world applications and other disciplines. Researchers and educators have indicated the importance of interdisciplinary science teaching for tackling complex global problems because these problems require insights from multiple disciplines to fully understand.[105–107] Some researchers in other disciplines have shown that ST enables students to produce an interdisciplinary understanding of a topic because students develop the cognitive abilities (e.g., critical thinking) necessary for fostering integration. Based on this evidence, chemistry educators have also suggested that ST can facilitate interdisciplinary teaching and learning.[12,78,108] To arrive at a sustainable solutions to global challenges that effectively use knowledge in chemistry, one needs to develop disciplinary skills outside of chemistry and collaborate with other scientists and non-science-based professions.[11,109] Therefore, chemistry educators may consider how to integrate interdisciplinary learning outcomes in their course when using a ST approach.

We also found that participants' believed ST gives a greater purpose to learning and allows students to engage in critical thinking. Two participants stated that ST activities may allow students to understand the importance of learning chemistry and help students build towards a future purpose or goal. Additionally, one participant indicated that a ST activity could promote critical thinking (Figure 19).

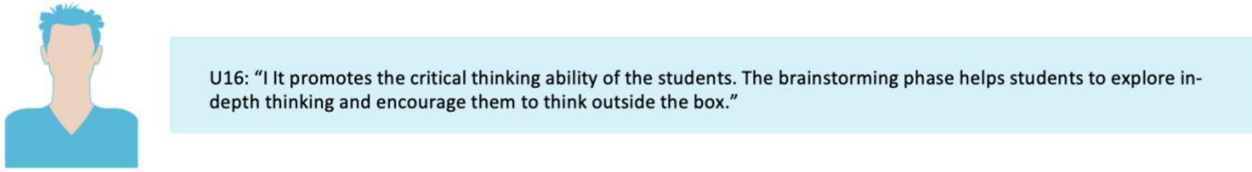


Figure 19. U16 quote.

This finding shows that ST tasks may promote students' critical thinking skills when students have opportunities to brainstorm concepts about a particular topic, which has been previously postulated.[106] Critical thinking is often experienced as a byproduct of interdisciplinary learning.[106] Given that ST and critical thinking are highlighted as skills required for 21st century jobs, both of these skills can be developed and practiced through interdisciplinary integration in chemistry courses.[20,21]

Systems thinking captures interest and engagement

Participants had enjoyable ST experiences and mentioned that ST may positively impact students' affective domain (e.g., feelings and attitudes). During the interviews, five participants indicated they had an overall enjoyable experience engaging in the ST intervention. These experiences may have influenced how they responded to the post-activity ST question. In their responses, they stated that ST will (1) help students' engagement, (2) make learning chemistry more interesting for students, and (3) capture students' interests. Participants believed that ST activities will make learning chemistry more interactive, interesting, and engaging for students who are not interested in chemistry (G4, Figure 20). G4 also indicated their interest with engaging in the ST tasks (SI 2.3, Theme 2). ST may be effective at capturing students' interest because it allows students to focus on the specific aspects of systems that they are passionate about (G8, Figure 20).

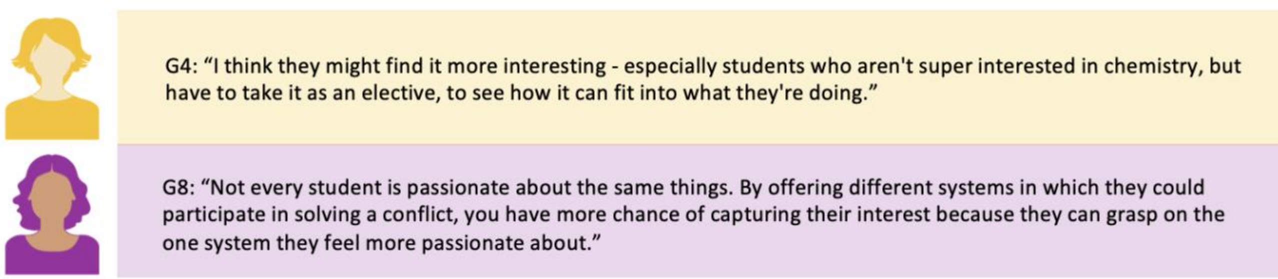


Figure 20. Participants quotes on students' interest (G4 and G8).

Collectively, these findings show that ST may improve student engagement and interest toward chemistry when students can connect chemistry to their personal lives and interests. Increased student engagement and interest have been reported as a potential benefit of ST as it encourages students to become personally involved in what they are learning.[17,110,111] Additionally, improving student engagement significantly predicts academic achievement in chemistry.[7] Given that effective student engagement is widely recognized as a critical educational objective, future research is needed to test these ST hypotheses on student engagement.

Systems thinking allows perspectives to be shared and gained.

Consistent with participants' ST experiences, participants believed that ST allows (1) students to share and gain perspectives with others and (2) participants to gain new perspectives about themselves. U11 indicated that collaborative ST activities are important for learning since they allow others to share and gain perspectives (Figure 21).

Figure 21. U11 quote.

Engagement with the ST tasks gave participants new perspectives about themselves. G7 mentioned that the ST tasks changed their way of thinking about making connections, which was different from how they listed their initial connections on the google form. Creating system maps allowed them to see the complexity of connections between concepts that they did not consider before and how they view things in different ways (Figure 22).

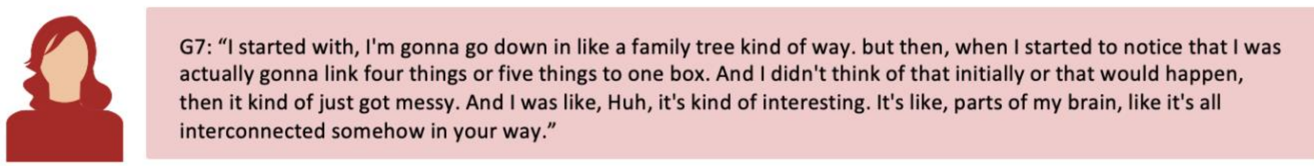


Figure 22. G7 quote.

Similar to the findings about students’ experience, G7 may have engaged in metacognitive processes to understand how they were making connections in their system maps. Perspective taking has been previously reported as an important skill of ST to understand how the various components in a system interconnect.[106] Our findings identify the potential significance of perspective taking for students and therefore should be considered in the design of ST activities.

Systems thinking provided personal, social and professional relevance

Participants indicated that ST provides: (1) professional relevance, allowing participants to view possible professions, (2) social relevance, clarifying chemistry’s purpose in human and social issues, and (3) personal relevance, allowing participants to make connections to their personal lives. Participants believed that ST could help students consider future career opportunities or fields of interest (professional relevance) (U4, Figure 23). Educators also believe that ST may expose students to less mainstream, career paths they may not have considered.[108] We also found that participants think ST can help other students identify the need for action to address climate change or work toward creating solutions to the issue (social relevance) (U17, Figure 23). Lastly, participants’ responses indicated ST may provide relevance to their own or others’ lives (personal relevance) (U9, Figure 23).

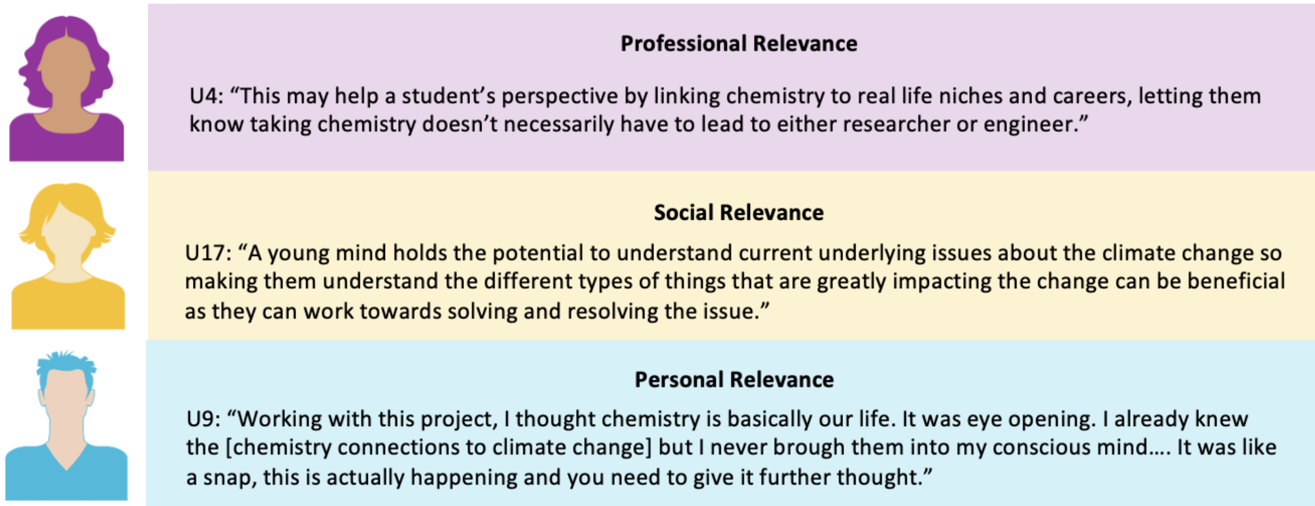


Figure 23. Examples of participants' quotes on professional, social, and personal relevance (U4, U17, and U9).

These findings show the potential for ST to make connections that are relevant to students¾ personally, socially, and professionally. When students can connect learning of chemistry to their personal lives, they may be more motivated or interested in learning the course content. However, introducing relevant context alone does not guarantee a productive learning experience which is why a ST approach needs to include opportunities to leverage students' other long-term individual interests.[111]

IMPLICATIONS FOR TEACHING AND RESEARCH

This work is one of the first in chemistry education to investigate student experiences of and perspectives toward using a ST approach in individual and collaborative chemistry education environments. Aligned with our second goal, we summarized the explicit connections our research findings have toward teaching practice and future research (Table 1). We aim to provide readers with efforts that should be considered when planning and implementing ST activities in chemistry and future work that needs to be conducted to better understand the impacts of ST in chemistry education.

Table 1. Summary of recommendations for ST instruction in chemistry and future chemistry education research

Recommendations for ST instruction in chemistry education
• Include explicit opportunities for students to share and gain diverse perspectives. • Allow students to develop adequate domain knowledge in class so that they can integrate this with their prior knowledge, experiences, and interests. • Explicitly highlight the role that chemistry concepts and processes play in the global issue. • Provide opportunities for students to use, articulate, and demonstrate ST skills in new contexts. • Consider integrating interdisciplinary learning outcomes to elicit ST and critical thinking skills. • If using systems maps in a ST activity, consider using a guided approach to teach students how to construct system maps. • Consider the different educational purposes for using system maps (e.g., presentation, brainstorming for personal learning and navigating connections) and avoid assessing the system map directly. • Provide scaffolding to support the use of online technologies and development of technology skills. • Considering timing require to complete ST activities or assessments.
Recommendations for future chemistry education research
• Investigate if using a ST approach can support active thinking, cognitive sophistication, and intellectual engagement when students with diverse perspectives interact. • Measure inclusion and equity outcomes of a collaborative ST approach in STEM education including, whether ST can (1) enhance the learning and success of all students, (2) support STEM innovation, (3) decrease disparities in academic success of underrepresented students, and (4) increase student retention and persistence in STEM programs. • Identify if ST approaches in chemistry education improve student engagement and leads to academic achievement.

CONCLUSIONS

We designed this study to better understand student perspectives of and experiences with ST, addressing an important gap in the literature on ST in education. In the study, the 26 undergraduate and graduate student participants had varying experiences. We found that sharing and gaining diverse perspectives may be an integral aspect of engaging with ST as this finding was highlighted in both student experiences and perspectives. We identified the potential impact that sharing and gaining diverse perspectives may have toward student learning and engagement as well as equity, diversity, and inclusion in chemistry education, which has yet to be investigated. Aligned with our research question on student experiences, we identified how students constructed and organized their system maps. Most students constructed their individual and group system maps by adding causes/effects and problems/solutions and used different organizational strategies. Students who purposefully organized their system maps through subtopics identified more interconnections among concepts compared to those who did not include subtopics. Participants intentionally made connections to chemistry in their system maps but indicated or demonstrated difficulties with making chemistry connections amongst concepts¾ highlighting an area of focus when implementing ST. Lastly, while students shared numerous beneficial experiences of constructing system maps, we identified several limitations related to time, knowledge, and technology skills.

Undergraduate and graduate students also expressed positive perspectives of a ST approach based on their experience engaging with ST tasks and believed a ST approach would positively influence other students if implemented in a chemistry course. Participants believed that ST: (1) is beneficial to learning, (2) captures interest and engagement, (3) allows perspectives to be shared and gained, and (4) provides personal, social, and professional relevance. This enthusiasm from students shows great promise for the potential of ST in chemistry education and support for its implementation in chemistry courses.

LIMITATIONS

There are several limitations to what we may conclude, given the study design and analysis procedures. First, while we were able to identify the perspectives and experiences of undergraduate and graduate students, due to our limited sample size, we could not distinguish between the two groups. Second, from our analysis we only uncovered positive perspectives from participants. A bias for socially preferred answers to questions (positive or negative) could have occurred. Participants may have wanted to help the research, so they refrained from expressing negative perspectives¾ an example of social desirability bias. That said, we looked for disconfirming evidence in the data and found none. Lastly, we identified perspectives and experiences of students who voluntarily engaged in a ST intervention separate from a course. Future studies would be needed to determine student perspectives and experiences when ST activities are implemented within a course and in different educational contexts.

ASSOCIATED CONTENT

Supporting Information

The SI includes more details about the methods, data analysis, and themes as well as the code books (*e.g.*, themes, description of themes, categories, and representative quotes) for this study. The ST intervention and interview are included for more context.

AUTHOR INFORMATION

Corresponding Author

*E-mail: alison.flynn@uottawa.ca

ACKNOWLEDGMENTS

ARS thanks Canada's Social Science and Humanities Research Council (SSHRC) for funding through a Canada Graduate Scholarship-Doctoral scholarship. We thank SSHRC for funding through an Insight Grant.

AUTHOR CONTRIBUTIONS

ARS, PGM, and ABF conceived the project and designed the initial research questions and methods. ARS collected the data. SB analyzed the first round of graduate interview data. ARS and ZR revised the research questions to better align with the data collected. ARS analyzed students' data collected from the interviews and verbal explanation from the group task. ZR analyzed students' written responses from the ST question in the post activity. All authors discussed the analysis, results, and conclusions. ZL wrote the first draft of the Results and Discussion for RQ2. ARS wrote the first draft for all other sections of the manuscript. ARS, ABF, and PGM edited and revised the manuscript.

CONFLICTS OF INTEREST

The authors declare there were no conflicts of interest.

REFERENCES

(1) Szozda, A. R.; Bruyere, K.; Lee, H.; Mahaffy, P. G.; Flynn, A. B. Investigating Educators' Perspectives toward Systems Thinking in Chemistry Education from International Contexts. *J. Chem. Educ.* **2022**, acs.jchemed.2c00138. https://doi.org/10.1021/acs.jchemed.2c00138.

(2) Hurst, G. A.; Slootweg, J. C.; Balu, A. M.; Climent-Bellido, M. S.; Gomera, A.; Gomez, P.; Luque, R.; Mammino, L.; Spanevello, R. A.; Saito, K.; Ibanez, J. G. International Perspectives on Green and Sustainable Chemistry Education via Systems Thinking. *J. Chem. Educ.* **2019**, *96* (12), 2794–2804. https://doi.org/10.1021/acs.jchemed.9b00341.

(3) Schultz, M.; Lai, J.; Ferguson, J. P.; Delaney, S. Topics Amenable to a Systems Thinking Approach: Secondary and Tertiary Perspectives. *J. Chem. Educ.* **2021**, *98* (10), 3100–3109. https://doi.org/10.1021/acs.jchemed.1c00203.

(4) Hutchison, J. E. Systems Thinking and Green Chemistry: Powerful Levers for Curricular Change and Adoption. *J. Chem. Educ.* **2019**, *96* (12), 2777–2783. https://doi.org/10.1021/acs.jchemed.9b00334.

(5) Petillion, R. J.; Freeman, T. K.; McNeil, W. S. United Nations Sustainable Development Goals as a Thematic Framework for an Introductory Chemistry Curriculum. *J. Chem. Educ.* **2019**, *96* (12), 2845–2851. https://doi.org/10.1021/acs.jchemed.9b00307.

(6) Summerton, L.; Clark, J. H.; Hurst, G. A.; Ball, P. D.; Rylott, E. L.; Carslaw, N.; Creasey, J.; Murray, J.; Whitford, J.; Dobson, B.; Sneddon, H. F.; Ross, J.; Metcalf, P.; McElroy, C. R. Industry-Informed Workshops to Develop Graduate Skill Sets in the Circular Economy Using Systems Thinking. *J. Chem. Educ.* **2019**, *96* (12), 2959–2967. https://doi.org/10.1021/acs.jchemed.9b00257.

(7) Ross, J.; Guerra, E.; Gonzalez-Ramos, S. Linking a Hierarchy of Attitude Effect to Student Engagement and Chemistry Achievement. *Chem. Educ. Res. Pract.* **2020**, *21* (1), 357–370. https://doi.org/10.1039/C9RP00171A.

(8) Mahaffy, P. G.; Krief, A.; Hopf, H.; Mehta, G.; Matlin, S. A. Reorienting Chemistry Education through Systems Thinking. *Nature Reviews Chemistry* **2018**, *2*, 0126. https://doi.org/10.1038/s41570-018-0126.

(9) *United Nations Sustainable Development Goals*. http://sustainabledevelopment.un.org/ (accessed 2019-11-11).

(10) Pazicni, S.; Flynn, A. B. Systems Thinking in Chemistry Education: Theoretical Challenges and Opportunities. *J. Chem. Educ.* **2019**, *96* (12), 2752–2763. https://doi.org/10.1021/acs.jchemed.9b00416.

(11) Matlin, S. A.; Mehta, G.; Hopf, H.; Krief, A. One-World Chemistry and Systems Thinking. *Nat. Chem.* **2016**, *8* (5), 393–398. https://doi.org/10.1038/nchem.2498.

(12) Mahaffy, P. G.; Matlin, S. A.; Holme, T. A.; MacKellar, J. Systems Thinking for Education about the Molecular Basis of Sustainability. *Nat. Sustain.* **2019**, *2* (5), 362–370. https://doi.org/10.1038/s41893-019-0285-3.

(13) Mahaffy, P. G.; Matlin, S. A.; Whalen, J. M.; Holme, T. A. Integrating the Molecular Basis of Sustainability into General Chemistry through Systems Thinking. *J. Chem. Educ.* **2019**, *96* (12), 2730–2741. https://doi.org/10.1021/acs.jchemed.9b00390.

(14) Holme, T. Chapter 2 - Incorporating Elements of Green and Sustainable Chemistry in General Chemistry via Systems Thinking. In *Integrating Green and Sustainable Chemistry Principles into Education*; Dicks, A. P., Bastin, L. D., Eds.; Elsevier, 2019; pp 31–47. https://doi.org/10.1016/B978-0-12-817418-0.00002-4.

(15) Anderson, J. *Experts on the Future of Work, Jobs Training and Skills*.

(16) World Economic Forum. *The Future of Jobs: Employment, Skills, and Workforce Strategy for the Fourth Industrial Revolution*; 2016. https://doi.org/10.23943/princeton/9780691172811.003.0009.

(17) York, S.; Fowler, W. C.; Orgill, M. K. Thoughts on Using Systems Thinking to Develop Chemistry Students' Professional Skills. *ACS Symp. Ser.* **2020**, *1365*, 81–102. https://doi.org/10.1021/bk-2020-1365.ch006.

(18) Overton, T.; McGarvey, D. J. Development of Key Skills and Attributes in Chemistry. *Chem Educ Res Pr.* **2017**, *18* (3), 401–402. https://doi.org/10.1039/C7RP90006F.

(19) Selvadurai, S.; Choy, E. A.; Maros, M. Generic Skills of Prospective Graduates from the Employers' Perspectives. *Asian Soc. Sci.* **2012**, *8* (12), 295–303. https://doi.org/10.5539/ass.v8n12p295.

(20) National Research Council. *Assessing 21st Century Skills: Summary of a Workshop*; National Academies Press: Washington, D.C., 2011; p 13215. https://doi.org/10.17226/13215.

(21) National Research Council. *Research on Future Skill Demands: A Workshop Summary*; National Academies Press: Washington, D.C., 2008.

(22) Child, S.; Shaw, S. Collaboration in the 21st Century: Implications for Assessment. *Res. Matters Camb. Assess. Publ.* **2016**, No. 22, 17–22.

(23) OECD. *Programme for International Student Assessment (PISA) 2015: Draft Collaborative Problem Solving Framework*. https://www.oecd.org/callsfortenders/Annex%20ID_PISA%202015%20Collaborative%20Problem%20Solving%20Framework%20.pdf.

(24) Verhoeff, R. P.; Knippels, M.-C. P. J.; Gilissen, M. G. R.; Boersma, K. T. The Theoretical Nature of Systems Thinking. Perspectives on Systems Thinking in Biology Education. *Front. Educ.* **2018**, *3* (40), 1–11. https://doi.org/10.3389/feduc.2018.00040.

(25) Assaraf, O. B.-Z.; Orion, N. Development of System Thinking Skills in the Context of Earth System Education. *J. Res. Sci. Teach.* **2005**, *42* (5), 518–560. https://doi.org/10.1002/tea.20061.

(26) Frank, M. Engineering Systems Thinking and Systems Thinking. *Syst. Eng.* **2000**, *3* (3), 163–168. https://doi.org/10.1002/1520-6858(200033)3:3<163::aid-sys5>3.3.co;2-k.

(27) Lavi, R.; Dori, Y. J. Systems Thinking of Pre- and in-Service Science and Engineering Teachers. *Int. J. Sci. Educ.* **2019**, *41* (2), 248–279. https://doi.org/10.1080/09500693.2018.1548788.

(28) Fanta, D.; Braeutigam, J.; Riess, W. Fostering Systems Thinking in Student Teachers of Biology and Geography – an Intervention Study. *J. Biol. Educ.* **2020**, *54* (3), 226–244. https://doi.org/10.1080/00219266.2019.1569083.

(29) *Systems Thinking in Chemistry for Sustainability: Towards 2030 and beyond (STCS 2030+)*. https://iupac.org/projects/project-details/?project_nr=2020-014-3-050 (accessed 2022-04-06).

(30) Evagorou, M.; Korfiatis, K.; Nicolaou, C.; Constantinou, C. An Investigation of the Potential of Interactive Simulations for Developing System Thinking Skills in Elementary School: A Case Study with Fifth-graders and Sixth-graders. *Int. J. Sci. Educ.* **2009**, *31* (5), 655–674. https://doi.org/10.1080/09500690701749313.

(31) Talanquer, V. Some Insights into Assessing Chemical Systems Thinking. *J. Chem. Educ.* **2019**. https://doi.org/10.1021/acs.jchemed.9b00218.

(32) York, S.; Orgill, M. ChEMIST Table: A Tool for Designing or Modifying Instruction for a Systems Thinking Approach in Chemistry Education. *J. Chem. Educ.* **2020**, *97* (8), 2114–2129. https://doi.org/10.1021/acs.jchemed.0c00382.

(33) Schmeck, R. R. An Introduction to Strategies and Styles of Learning. In *Learning Strategies and Learning Styles*; Springer Science+Business Media: New York, NY, 1988; pp 3–19.

(34) Schmeck, R. R. Strategies and Styles of Learning: An Integration of Varied Perspectives. In *Learning Strategies and Learning Styles*; Springer Science+Business Media: New York, NY, 1988; pp 317–347.

(35) Kirby, J. R. Style, Strategy, and Skill in Reading. In *Learning Strategies and Learning Styles*; Springer Science+Business Media: New York, NY, 1988; pp 229–274.

(36) Marton, F. Describing and Improving Learning. In *Learning Strategies and Learning Styles*; Springer Science+Business Media: New York, NY, 1988; pp 53–82.

(37) Tripto, J.; Assaraf, O. B.-Z.; Amit, M. Mapping What They Know: Concept Maps as an Effective Tool for Assessing Students' Systems Thinking. *Am. J. Oper. Res.* **2013**, *03* (01), 245–258. https://doi.org/10.4236/ajor.2013.31A022.

(38) Sweeney, L. B.; Sterman, J. D. Thinking about Systems: Student and Teacher Conceptions of Natural and Social Systems. *Syst. Dyn. Rev.* **2007**, *23* (2–3), 285–311. https://doi.org/10.1002/sdr.366.

(39) Assaraf, O. B.-Z.; Orion, N. Development of System Thinking Skills in the Context of Earth System Education. *J. Res. Sci. Teach.* **2005**, *42* (5), 518–560. https://doi.org/10.1002/tea.20061.

(40) Verhoeff, R. P.; Knippels, M.-C. P. J.; Gilissen, M. G. R.; Boersma, K. T. The Theoretical Nature of Systems Thinking. Perspectives on Systems Thinking in Biology Education. *Front. Educ.* **2018**, *3*, 40. https://doi.org/10.3389/feduc.2018.00040.

(41) Hmelo, C. E.; Holton, D. L.; Kolodner, J. L. Designing to Learn About Complex Systems. *J. Learn. Sci.* **2000**, *9* (3), 247–298. https://doi.org/10.1207/S15327809JLS0903_2.

(42) Szozda, A. R.; Mahaffy, P. G.; Flynn, A. B. Identifying Chemistry Students' Baseline Systems Thinking Skills When Constructing System Maps for a Topic on Climate Change. *J. Chem. Educ.*

(43) Mahaffy, P. G.; Martin, B.; Hoffman, M.; MacDonald, R. P.; Elgersma, A. K.; Lasola, K.; Gagnon, A.; Ciezki, A.; Tilstra, M.; Vanderwekken, L.; Keeler, T.; Schwalfenberg, A.; Vandenbrink, D.; Zondervan, J. *Design Our Climate Simulation*. https://climatesolutions.kcvs.ca (accessed 2022-12-15).

(44) Patton, M. Q. Qualitative Interviewing. In *Qualitative Research & Evaluation Methods*; SAGE Publications, Inc.: Thousand Oaks, California, 2015; pp 421–517.

(45) Creswell, J. W. *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*; Pearson: Boston, MA, USA, 2012.

(46) Auerbach, C. F.; Silverstein, L. B. *Qualitative Data: An Introduction to Coding and Analysis.*; Qualitative studies in psychology.; New York University Press: New York, NY, US, 2003.

(47) Boyatzis, R. E. *Transforming Qualitative Information: Thematic Analysis and Code Development.*; Sage Publications, Inc: Thousand Oaks, CA, US, 1998.

(48) Lincoln, Y. S.; Guba, E. G.; Pilotta, J. J. *Naturalistic Inquiry*; Newbury Park, CA: Sage., 1985.

(49) Saldaña, J. *The Coding Manual for Qualitative Researchers*, 3rd ed.; SAGE Publications, Inc.: Thousand Oaks, California, 2016.

(50) Creswell, J. W.; Miller, D. L. Determining Validity in Qualitative Inquiry. *Theory Pract.* **2000**, *39* (3), 124–130. https://doi.org/10.1207/s15430421tip3903_2.

(51) Schunk, D. H. *Learning Theories: An Educational Perspective (6th Edition)*; Pearson Education Inc: Boston, MA, 2012; Vol. 5.

(52) Mayer, R. E. Information Processing. In *APA educational psychology handbook, Vol 1: Theories, constructs, and critical issues.*; APA handbooks in psychology®.; American Psychological Association: Washington, DC, US, 2012; pp 85–99. https://doi.org/10.1037/13273-004.

(53) Pazicni, S.; Flynn, A. B. Systems Thinking in Chemistry Education: Theoretical Challenges and Opportunities. *J. Chem. Educ.* **2019**, *96* (12), 2752–2763. https://doi.org/10.1021/acs.jchemed.9b00416.

(54) Galloway, K. R.; Stoyanovich, C.; Flynn, A. B. Students' Interpretations of Mechanistic Language in Organic Chemistry before Learning Reactions. *Chem. Educ. Res. Pract.* **2017**, *18* (2), 353–374. https://doi.org/10.1039/C6RP00231E.

(55) Bretz, S. L. Novak's Theory of Education: Human Constructivism and Meaningful Learning. *J. Chem. Educ.* **2001**, *78* (8), 1107. https://doi.org/10.1021/ed078p1107.6.

(56) Schunk, D. H. *Learning Theories: An Educational Perspective*, 6th ed.; Pearson: Boston, 2012.

(57) Vygotsky, L. S. *Mind in Society*; Cole, M., Jolm-Steiner, V., Scribner, S., Souberman, E., Series Eds.; Harvard University Press, 1978. https://doi.org/10.2307/j.ctvjf9vz4.

(58) Tudge, J.; Scrimsher, S. Lev S. Vygotsky on Education: A Cultural-Historical, Interpersonal, and Individual Approach to Development. In *Educational Psychology: A Century of Contributions: A Project of Division 15 (educational Psychology) of the American Psychological Society*; Routledge, 2002; p 22.

(59) King, J. Asked Students to Share Ideas and Experiences with Others Whose Backgrounds and Viewpoints Differ from Their Own.

(60) Meacham, J.; McClellan, M.; Pearse, T.; Green, R. Student Diversity in Classes and Edcuational Outcomes: Student Perceptions. *Coll. Stud. J.* **2003**.

(61) Goethe, E. V.; Colina, C. M. Taking Advantage of Diversity within the Classroom. *J. Chem. Educ.* **2018**, *95* (2), 189–192. https://doi.org/10.1021/acs.jchemed.7b00510.

(62) Gurin, P.; Dey, E.; Hurtado, S.; Gurin, G. Diversity and Higher Education: Theory and Impact on Educational Outcomes. *Harv. Educ. Rev.* **2002**, *72* (3), 330–367. https://doi.org/10.17763/haer.72.3.01151786u134n051.

(63) Marin, P. The Educational Possibility of Multi-Racial/MultiEthnic College Classrooms. In *In Does Diversity Make a Difference? Three Research Studies on Diversity in College Classrooms*; American Council on Education and American Association of University Professors: Washington, DC, 2000; pp 61–83.

(64) Antonio, A. L.; Chang, M. J.; Hakuta, K.; Kenny, D. A.; Levin, S.; Milem, J. F. Effects of Racial Diversity on Complex Thinking in College Students. *Psychol. Sci.* **2004**, *15* (8), 507–510. https://doi.org/10.1111/j.0956-7976.2004.00710.x.

(65) Yershova, Y.; Dejaeghere, J.; Mestenhauser, J. Thinking Not a Usual: Adding the Intercultural Perspective. *J. Stud. Int. Educ. - J STUD INT EDUC* **2000**, *4*, 39–78. https://doi.org/10.1177/102831530000400105.

(66) Schultz, M.; Chan, D.; Eaton, A. C.; Ferguson, J. P.; Houghton, R.; Ramdzan, A.; Taylor, O.; Vu, H. H.; Delaney, S. Using Systems Maps to Visualize Chemistry Processes: Practitioner and Student Insights. *Educ. Sci.* **2022**, *12* (9), 596. https://doi.org/10.3390/educsci12090596.

(67) Homan, A. C.; Van Knippenberg, D.; Van Kleef, G. A.; De Dreu, C. K. W. Bridging Faultlines by Valuing Diversity: Diversity Beliefs, Information Elaboration, and Performance in Diverse Work Groups. *J. Appl. Psychol.* **2007**, *92* (5), 1189–1199. https://doi.org/10.1037/0021-9010.92.5.1189.

(68) White, K. N.; Vincent-Layton, K.; Villarreal, B. Equitable and Inclusive Practices Designed to Reduce Equity Gaps in Undergraduate Chemistry Courses. *J. Chem. Educ.* **2021**, *98* (2), 330–339. https://doi.org/10.1021/acs.jchemed.0c01094.

(69) Wilson, Z. S.; McGuire, S. Y.; Limbach, P. A.; Doyle, M. P.; Marzilli, L. G.; Warner, I. M. Diversifying Science, Technology, Engineering, and Mathematics (STEM): An Inquiry into Successful Approaches in Chemistry. *J. Chem. Educ.* **2014**, *91* (11), 1860–1866. https://doi.org/10.1021/ed400702v.

(70) Milliken, F. J.; Martins, L. L. Searching for Common Threads: Understanding the Multiple Effects of Diversity in Organizational Groups. *Acad. Manage. Rev.* **1996**, *21* (2), 402. https://doi.org/10.2307/258667.

(71) Novak, J. D. Human Constructivism: A Unification of Psychological and Epistemological Phenomena in Meaning Making. *Int. J. Pers. Constr. Psychol.* **1993**, *6* (2), 167–193. https://doi.org/10.1080/08936039308404338.

(72) Novak, J. D. Learning, Creating, and Using Knowledge: Concept Maps as Facilitative Tools in Schools and Corporations. *J. E-Learn. Knowl. Soc.* **2010**, *6* (3), 21–30. https://doi.org/10.5860/CHOICE.36-1103.

(73) Panitz, T. The Motivational Benefits of Cooperative Learning. *New Dir. Teach. Learn.* **1999**, *1999* (78), 59–67. https://doi.org/10.1002/tl.7806.

(74) Johnson, D. W.; Johnson, R. T. *Cooperation and Competition: Theory and Research*; Interaction Book Company: Edina, MN, USA, 1989.

(75) Laal, M.; Ghodsi, S. M. Benefits of Collaborative Learning. *Procedia - Soc. Behav. Sci.* **2012**, *31*, 486–490. https://doi.org/10.1016/j.sbspro.2011.12.091.

(76) Bodé, N. E.; Deng, J. M.; Flynn, A. B. Getting Past the Rules and to the WHY: Causal Mechanistic Arguments When Judging the Plausibility of Organic Reaction Mechanisms. *J. Chem. Educ.* **2019**, *96* (6), 1068–1082. https://doi.org/10.1021/acs.jchemed.8b00719.

(77) Spaeth, E.; He, A.; Pearson, A. A Reflective Analysis on How to Promote a Positive Learning Experience for Neurodivergent Students. *J. Perspect. Appl. Acad. Pract.* **2023**, *11* (2).

(78) Flynn, A. B.; Orgill, M.; Ho, F. M.; York, S.; Matlin, S. A.; Constable, D. J. C.; Mahaffy, P. G. Future Directions for Systems Thinking in Chemistry Education: Putting the Pieces Together. *J. Chem. Educ.* **2019**, *96* (12), 3000–3005. https://doi.org/10.1021/acs.jchemed.9b00637.

(79) Theobald, E. J.; Hill, M. J.; Tran, E.; Agrawal, S.; Arroyo, E. N.; Behling, S.; Chambwe, N.; Cintrón, D. L.; Cooper, J. D.; Dunster, G.; Grummer, J. A.; Hennessey, K.; Hsiao, J.; Iranon, N.; Jones, L.; Jordt, H.; Keller, M.; Lacey, M. E.; Littlefield, C. E.; Lowe, A.; Newman, S.; Okolo, V.; Olroyd, S.; Peecook, B. R.; Pickett, S. B.; Slager, D. L.; Caviedes-Solis, I. W.; Stanchak, K. E.; Sundaravardan, V.; Valdebenito, C.; Williams, C. R.; Zinsli, K.; Freeman, S. Active Learning Narrows Achievement Gaps for Underrepresented Students in Undergraduate Science, Technology, Engineering, and Math. *Proc. Natl. Acad. Sci.* **2020**, *117* (12), 6476–6483. https://doi.org/10.1073/pnas.1916903117.

(80) Estrada, M.; Burnett, M.; Campbell, A. G.; Campbell, P. B.; Denetclaw, W. F.; Gutiérrez, C. G.; Hurtado, S.; John, G. H.; Matsui, J.; McGee, R.; Okpodu, C. M.; Robinson, T. J.; Summers, M. F.; Werner-Washburne, M.; Zavala, M. Improving Underrepresented Minority Student Persistence in STEM. *CBE—Life Sci. Educ.* **2016**, *15* (3), es5. https://doi.org/10.1187/cbe.16-01-0038.

(81) Estrada, M.; Woodcock, A.; Hernandez, P. R.; Schultz, P. W. Toward a Model of Social Influence That Explains Minority Student Integration into the Scientific Community. *J. Educ. Psychol.* **2011**, *103* (1), 206–222. https://doi.org/10.1037/a0020743.

(82) Freeman, S.; Eddy, S. L.; McDonough, M.; Smith, M. K.; Okoroafor, N.; Jordt, H.; Wenderoth, M. P. Active Learning Increases Student Performance in Science, Engineering, and Mathematics. *Proc. Natl. Acad. Sci.* **2014**, *111* (23), 8410–8415. https://doi.org/10.1073/pnas.1319030111.

(83) Dewsbury, B. M.; Swanson, H. J.; Moseman-Valtierra, S.; Caulkins, J. Inclusive and Active Pedagogies Reduce Academic Outcome Gaps and Improve Long-Term Performance. *PLOS ONE* **2022**, *17* (6), e0268620. https://doi.org/10.1371/journal.pone.0268620.

(84) Valdez, C. J.; Kelp, N. C. Student Perceptions of Inclusive Pedagogy in Undergraduate STEM Classrooms. *J. Microbiol. Biol. Educ.* **2023**, e00097-23. https://doi.org/10.1128/jmbe.00097-23.

(85) Johnson, K. M. S. Implementing Inclusive Practices in an Active Learning STEM Classroom. *Adv. Physiol. Educ.* **2019**, *43* (2), 207–210. https://doi.org/10.1152/advan.00045.2019.

(86) Talanquer, V. Progressions in Reasoning about Structure–Property Relationships. *Chem. Educ. Res. Pract.* **2018**, *19* (4), 998–1009. https://doi.org/10.1039/C7RP00187H.

(87) Kozma, R. B.; Russell, J. Multimedia and Understanding: Expert and Novice Responses to Different Representations of Chemical Phenomena. *Journal of Research in Science Teaching* **1997**, *34*, 949–968. https://doi.org/10.1002/(SICI)1098-2736(199711)34:9<949::AID-TEA7>3.0.CO;2-U.

(88) Johnstone, A. H. Teaching of Chemistry - Logical or Psychological? *Chem Educ Res Pr.* **2000**, *1* (1), 9–15. https://doi.org/10.1039/A9RP90001B.

(89) Strickland, A. M.; Kraft, A.; Bhattacharyya, G. What Happens When Representations Fail to Represent? Graduate Students' Mental Models of Organic Chemistry Diagrams. *Chem Educ Res Pr.* **2010**, *11* (4), 293–301. https://doi.org/10.1039/C0RP90009E.

(90) Davidowitz, B.; Chittleborough, G. Linking the Macroscopic and Sub-Microscopic Levels: Diagrams. In *Multiple Representations in Chemical Education*; Gilbert, J. K., Treagust, D., Eds.; Springer Netherlands: Dordrecht, 2009; pp 169–191. https://doi.org/10.1007/978-1-4020-8872-8_9.

(91) Deng, J. M.; Flynn, A. B. Reasoning, Granularity, and Comparisons in Students' Arguments on Two Organic Chemistry Items. *Chem. Educ. Res. Pract.* **2021**, *22* (3), 749–771. https://doi.org/10.1039/D0RP00320D.

(92) Talanquer, V. Macro, Submicro, and Symbolic: The Many Faces of the Chemistry "Triplet." *Int. J. Sci. Educ.* **2011**, *33* (2), 179–195. https://doi.org/10.1080/09500690903386435.

(93) Johnstone, A. H. Macro- and Microchemistry. *Sch. Sci. Rev.* **1982**, *64*, 377–379.

(94) Hannafin, M. J.; Land, S. M. Technology and Student-Centered Learning in Higher Education: Issues and Practices. *J. Comput. High. Educ.* **2000**, *12* (1), 3–30. https://doi.org/10.1007/BF03032712.

(95) Spiro, R.; Feltovich, P.; Jacobson, M.; Coulson, R. Cognitive Flexibility, Constructivism, and Hypertext: Random Access Instruction for Advanced Knowledge Acquisition in Ill-Structured Domains. *Educ. Technol.* **1991**, No. 5, 24–33.

(96) Bransford, J.; Franks, J.; Vye, N.; Sherwood, R. New Approaches to Instruction: Because Wisdom Can't Be Told. In *Similarity and analogical reasoning*; Cambridge University Press: New York, 1989; pp 470–497.

(97) Royer, J. M. Theories of the Transfer of Learning. *Educ. Psychol.* **1979**, *14* (1), 53–69.

(98) Chemistry Education Needs a Green Reset. *Nature* **2022**, *604* (598). https://doi.org/10.1038/d41586-022-01109-z.

(99) Mahaffy, P. G.; Brush, E. J.; Haack, J. A.; Ho, F. M. *Journal of Chemical Education* Call for Papers—Special Issue on Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry. *J. Chem. Educ.* **2018**, *95* (10), 1689–1691. https://doi.org/10.1021/acs.jchemed.8b00764.

(100) King's Centre for Visualization in Science. *SOCKit*. https://applets.kcvs.ca/sockit/index.html (accessed 2023-11-24).

(101) Liu, M.; McKelroy, E.; Corliss, S. B.; Carrigan, J. Investigating the Effect of an Adaptive Learning Intervention on Students' Learning. *Educ. Technol. Res. Dev.* **2017**, *65* (6), 1605–1625. https://doi.org/10.1007/s11423-017-9542-1.

(102) Howlin, C. Realizeit at the University of Central Florida: Results from Initial Trials of Realizeit at the University of Central Florida, 2014. https://cdl.ucf.edu/staticfiles/online/visitor/Personalized%20Learning/RealizeIt%20at%20the%20University%20of%20Central%20Florida.pdf.
(103) Gillett-Swan, J. Supporting and Engaging the Isolated Learner. *J. Learn. Des.* **2017**, *10* (1).
(104) Soloway, E.; Krajcik, J.; Bkumenfeld, P.; Marx, R. Technological Support for Teachers Transitioning to Project-Based Science Practices. In *CSCL" Theory and practice of an emerging paradigm*; Lawrence Erlbaum Associates: Mahwah, NJ, 1996; pp 269–306.
(105) You, H. S. Why Teach Science with an Interdisciplinary Approach: History, Trends, and Conceptual Frameworks. *J. Educ. Learn.* **2017**, *6* (4), 66. https://doi.org/10.5539/jel.v6n4p66.
(106) Mathews, L. G. Reflections on a Pilot Study in Land Economics. 32.
(107) Fisher, D. Reflections on Teaching System Dynamics Modeling to Secondary School Students for over 20 Years. *Systems* **2018**, *6* (2), 12. https://doi.org/10.3390/systems6020012.
(108) Jackson, A.; Hurst, G. A. Faculty Perspectives Regarding the Integration of Systems Thinking into Chemistry Education. *Chem. Educ. Res. Pract.* **2021**, *22* (4), 855–865. https://doi.org/10.1039/D1RP00078K.
(109) Constable, D. J. C. Green and Sustainable Chemistry – The Case for a Systems-Based, Interdisciplinary Approach. *iScience* **2021**, *24* (12), 103489. https://doi.org/10.1016/j.isci.2021.103489.
(110) Sweeney, L. B. How Is This Similar to That? 10.
(111) Ke, L.; Sadler, T. D.; Zangori, L.; Friedrichsen, P. J. Students' Perceptions of Socio-Scientific Issue-Based Learning and Their Appropriation of Epistemic Tools for Systems Thinking. *Int. J. Sci. Educ.* **2020**, *42* (8), 1339–1361. https://doi.org/10.1080/09500693.2020.1759843.