

**Investigating Systems Thinking in Chemistry Education:
Students' and Educators' Experiences and Perspectives**

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Abstract

Chemistry knowledge is essential in addressing solutions to complex global challenges such as achieving the United Nations' Sustainable Development Goals (SDGs), which include climate action, good health and well-being, and quality education. However, chemistry knowledge is often taught in silos of individual topics to achieve a depth of understanding, placing less emphasis on making connections to other disciplines or global issues. Calls have been made to reimagine how chemistry is taught so that citizens and chemists can contribute to solutions to these complex global challenges. Researchers and educators have been exploring systems thinking (ST), which has been proposed as part of an approach to chemistry education. ST aims to understand and interpret complex problems from a holistic perspective. ST has a goal to better equip citizens and future scientists for the interdisciplinary work needed to address these emerging global issues. However, there has been limited evidence-based research on what ST looks like or its impact on chemistry education. Without evidence, uncertainty will persist on how to effectively implement ST in chemistry education and wide-spread implementation will remain a challenge, limiting the ability to equip people with the knowledge and skills to understand and solve these global challenges.

My doctoral thesis has contributed to this area of need by investigating students' and educators' perspectives and experiences of ST approaches in chemistry education. We found 56 chemistry educators' willingness and ability to implement ST in chemistry education is influenced by their knowledge, beliefs, experiences, contextual and personal factors (Chapter 2). Additionally, barriers related to educators' knowledge on ST and contextual factors (e.g., limited time to learn and teach ST, limited teaching resources and assessments) were rated the highest among educators. This work can guide priorities for educational change efforts to reduce barriers for implementing ST in chemistry education.

In addition to learning about educators' perspectives and experiences with ST in chemistry education, we investigated students' perspectives and experiences when engaging in ST tasks, as they are also key stakeholders who must be considered when implementing ST. We created a ST intervention in which 26 undergraduate and graduate students, taking chemistry courses, engaged in three ST tasks and interviews. We identified ST skills that these students do and do not demonstrate readily, to understand which skills need to be explicitly scaffolded in their instruction (Chapter 3). While most students demonstrated most of the 11 ST skills assessed, some aspects of the skills were demonstrated less frequently, drawing attention to areas that need to be explicitly taught and scaffolded. The aspects demonstrated less frequently in students' systems maps include: (1) fewer concepts and connections at

submicroscopic levels of granularity (e.g., molecular, atomic, subatomic), (2) limited circular loops and causal connections, and (3) no connections that considered human impact on chemistry. This work was one of the first that provided some understanding of how to assess ST skills in chemistry education.

The research in Chapter 4 explored students' experiences more broadly by looking at their engagement with individual and collaborative ST tasks during the intervention and identifying aspects of ST that may be beneficial and challenging for students. Students shared more positive than negative experiences with the ST tasks. One beneficial experience was recognizing and appreciating different perspectives and ideas from their group members, bringing attention to important implications related to equity, diversity, and inclusion in chemistry education. We also found that students had varying positive perspectives based on their engagement with the ST tasks and their perspectives of other students engaging with ST in a chemistry course. Implications of this work include specific recommendations on how to approach ST instruction for chemistry teaching and learning.

These recommendations were considered in the design of a new ST study to investigate the impact of using a ST approach to support the evaluation of scientific misinformation (Chapter 5). In addition to the chemistry education research in Chapters 2 to 4, my doctoral degree focused on curriculum development by using some of these research findings to inform the development of a ST framework, helping educators to plan, implement, and assess ST in chemistry education (Chapter 6).

We have made significant contributions to areas of ST that had not been previously explored, creating momentum for future research on ST in chemistry education. There are still many research opportunities on ST needed to explore cognitive and affective outcomes as well as EDI and long-term transfer of knowledge and skills in chemistry. Our research has helped identified **what** ST looks like in chemistry education, now educators and researchers can use this knowledge to investigate **how** ST approaches impact the field.

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chemistry education. I also want to deeply thank Dr. David Laviska for inviting me to attend the 2nd Annual ACS Sustainability Summit: Reimagining Chemistry Education where I was able to contribute to important discussions on ST and sustainability and gave me the opportunity to connect with many esteemed people from academia, industry, and non-government organizations. Lastly, I am thankful for the opportunity to co-organize the ST workshop at the International Conference on Chemistry Education with Dr. Peter Mahaffy, Dr. Seamus Delaney, Dr. Vicente Talanquer, and Dr. David Laviska. This was my first experience conducting a formal workshop and it was such a fun experience.

To all the people I met at the conferences I attended, thank you for the friendships created at these conferences, thank you for the questions during my talks, and thank you for all the wonderful conversations. These connections were a highlight of my degree, and I look forward to staying connected with these communities in the future.

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Overview of Academic Contributions

My strong passion for chemistry education goes beyond being a chemistry education researcher. My career has been characterized and guided by my passion to provide access to educational opportunities that equip all learners with skills essential for the 21st century.

I have significant experience leading educational development and outreach efforts focused on the support and implementation of teaching and learning resources. As a result of over 10 years of teaching in secondary and post-secondary education, I shared my expertise as co-first author on the book, “Remote Teaching: A Guide for Teaching Assistants.”¹ This book is an Open Educational Resource designed to provide TAs from all departments in science with teaching approaches and strategies to transition to a remote teaching environment and has been accessed over 4000 times on six continents.

My continued efforts to support TAs were demonstrated through my role as a co-organizer of the TA Workshop development team at the University of Ottawa.² I worked closely with faculty members and graduate students to provide TAs with synchronous workshops to practice the skills and teaching approaches that are explained in the book. This work led to a Transition to Online and Distance Teaching TA award. Most recently, I have co-constructed curriculum resources and an educational framework to support educators worldwide in planning, implementing, and assessing systems thinking in their courses.³ This educational framework has been published in the Journal of Chemical Education and has been viewed over 2700 times.⁴

Science communication is also an essential aspect of research to me—I presented my research at four local, seven national, and eleven international scientific conferences and published four peer-reviewed articles in the Journal of Chemical Education, three of those as first author. I demonstrated academic leadership over the years by co-chairing a local conference, *Ottawa-Carleton Chemistry Institute Day 2021* and organizing an educational seminar series for graduate students and Faculty at the University of Ottawa and Carleton University. I chaired symposia at a National conference, *Canadian Chemistry Conference and Exhibition 2024* and presided over a symposium at an international chemistry education conference, *Biennial Conference of Chemistry Education 2022*. In 2020–2021, my contributions were recognized when I was selected as a *Remarkable Student* in the Faculty of Science at uOttawa.

Beyond my research, I have been involved in various committees locally and internationally. I was elected as one of two graduate students to serve on the *Senate Committee of Teaching and Teaching Evaluation* at the University of Ottawa for four years. For three years, I have served on the executive committees for the uOttawa *Canadians Working for Inclusivity in Chemistry* chapter and the uOttawa *Chemistry and Biomolecular Graduate Students’ Association*. I was also a mentor for the *Chemistry*

Buddy Program for three years. Over the last year, I was a member of the project team: *IUPAC Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond*, the only graduate student member on that team to date.

Teaching is one of my greatest passions. In addition to being a teaching assistant for general chemistry, organic chemistry I and II laboratory and theory courses, I have been a guest instructor for general chemistry and organic chemistry II theory courses. While completing my degree, I also taught a semester of grade 12 chemistry at a local high school in 2020 and a General, Organic, and Biological Chemistry course at Algonquin College in 2024. My teaching has been recognized through several TA awards. I received a uOttawa Faculty of Science TA of the year award (2020-2021) and uOttawa Department of Chemistry and Biomolecular Science TA of the year award (2022-2023).

Overall, I have made significant contributions to educational research, development, teaching, and outreach throughout my degree.

References

- (1) Allen, M.; Szozda, A. R.; Kerr, J.; Flynn, A. B. *Remote Teaching: A Guide for Teaching Assistants*; eCampusOntario: University of Ottawa; Ottawa, ON, 2020.
- (2) Flynn, Alison. B.; Szozda, A. R. *Ateliers pour AEs / TA workshops*. Padlet. <https://padlet.com/alisonflynn/ateliers-pour-aes-ta-workshops-24tfljngz32q9o77> (accessed 2024-08-09).
- (3) *Sustainability and Systems Thinking in Chemistry Education*. <https://sastice.com/> (accessed 2024-01-25).
- (4) Talanquer, V.; Szozda, A. R. An Educational Framework for Teaching Chemistry Using a Systems Thinking Approach. *J. Chem. Educ.* **2024**, *101* (5), 1785–1792. <https://doi.org/10.1021/acs.jchemed.4c00216>.

List of Contributions

Publications

1. **Szozda, A. R.;** Lalani, Z.; Behroozi, S.; Mahaffy, P. G.; Flynn, A. B. “Systems thinking encourages a safe space to offer different perspectives and insights”: Students’ perspectives of and experiences with individual and collaborative ST activities in chemistry education. *J. Chem. Educ.* **2024**, 101, 6, 2290-2307. doi.org/10.1021/acs.jchemed.4c00080
2. Talanquer, V.; **Szozda, A. R.** “An Educational Framework for Teaching Chemistry Using a Systems Thinking Approach. *J. Chem. Educ.* **2024**, 101, 5, 1785–1792. doi.org/10.1021/acs.jchemed.4c00216
3. **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. Identifying chemistry students’ baseline systems thinking skills when constructing systems for a topic on climate change. *J. Chem. Educ.* **2023**, 100, 5, 1763–1776. pubs.acs.org/doi/10.1021/acs.jchemed.2c00955
4. Deng, J. M.; Lalani, Z. McDermaid, L. A.; **Szozda, A. R.** Using generative artificial intelligence safely and ethically in chemistry education research. *J. Chem. Educ. Submitted. 2023. Available as a preprint on ChemRxiv* [10.26434/chemrxiv-2023-24zfl](https://doi.org/10.26434/chemrxiv-2023-24zfl)
5. **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**, 99, 7, 2474–2483. doi.org/10.1021/acs.jchemed.2c00138.

Books

1. Allen, M; **Szozda, A**; Kerr, J; Flynn, B. A. *Remote Teaching: A Guide for Teaching Assistants*. eCampusOntario: University of Ottawa; Ottawa, ON, 2020. Available from [English](#) | [Français](#).

Presentations and Workshops

* Abstracts accepted but conferences were cancelled due to COVID-19 pandemic.

** Invited Presentations.

International

1. **Szozda, A. R.;** Lalani, Z.; Behroozi, S.; Mahaffy, P. G.; Flynn, A. B. Cultivating students’ diverse perspectives into the curricular design of systems thinking in chemistry education activities. ***International Conference on Chemistry Education*** (oral), Pattaya, Thailand, July 2024.
2. Talanquer, V.; **Szozda, A. R.** (co-presented) An educational framework for teaching chemistry using a systems thinking approach. ***International Conference on Chemistry Education*** (oral), Pattaya, Thailand, July 2024.
3. Mahaffy, P.G.; Delaney, S.; Talanquer, V.; **Szozda, A. R.;** Laviska, D. (co-presented) Getting systems thinking into your classroom and connecting to sustainability. ***International Conference on Chemistry Education*** (workshop), Pattaya, Thailand, July 2024.
4. ** Szozda, A. R. **2nd Annual ACS Sustainability Summit: Reimagining Chemistry Education** (Invited Attendee to contribute to discussions), Washington D.C., United States, December 2023.
5. **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. Using climate change system maps to identify chemistry students’ baseline systems thinking skills. ***Gordon Research Conference – Visualization in Science and Education*** (Poster), Maine, United States, July 2023.
6. **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. Identifying chemistry students’ baseline systems thinking skills when constructing system maps of climate change. ***Gordon Research Conference – Chemistry Education Research and Practice*** (Poster), Maine, United States, July 2023.

7. **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. Identifying chemistry students' baseline systems thinking skills when constructing system maps of climate change. ***Gordon Research Seminar – Chemistry Education Research and Practice*** (Poster), Maine, United States, July 2023.
8. ** Szozda, A. R. Investigating systems thinking in chemistry education: student approaches and educator perspectives. ***Graulich Group Seminar*** (Oral, online), Justus-Liebig-Universität Gießen, Germany, January 2023.
9. **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. ***2022 Biennial Conference on Chemical Education*** (Oral), Indiana, United States, August 2022.
10. **Szozda, A. R.;** Bruyere, K.; Lee, H.; Mahaffy, P. G.; Flynn, A. B. Investigating how chemists engage in systems thinking in chemistry education. ***Methods in Chemistry Education Research*** (Poster, online), June 2021.
11. * **Szozda, A. R.;** Bruyere, K.; Lee, H.; Mahaffy, P. G.; Flynn, A. B. Investigating the effect of a systems thinking intervention oriented towards the molecular basis of sustainability: An exploratory study. ***2020 Biennial Conference on Chemical Education*** (Oral).

National

1. ** **Szozda, A. R.;** Lalani, Z.; Behroozi, S.; Mahaffy, P. G.; Flynn, A. B. "Systems thinking encourages a safe space to offer different perspectives and insights": Student perspectives and experiences with individual and collaborative systems thinking activities. ***107th Canadian Chemistry Conference and Exhibition*** (Oral), Winnipeg, Manitoba, June 2024.
2. **Szozda, A. R.;** Talanquer, V. Planning, Implementing, and Assessing Systems Thinking in Chemistry Education. ***107th Canadian Chemistry Conference and Exhibition*** (Oral), Winnipeg, Manitoba, June 2024.
3. **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. ***106th Canadian Chemistry Conference and Exhibition*** (Oral), Vancouver, British Columbia, June 2023.
4. **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. What skills do students use when engaging in systems thinking in chemistry education learning activities on climate change? ***105th Canadian Chemistry Conference and Exhibition*** (Oral), Calgary, Alberta, June 2022.
5. **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. Investigating how students engage in systems thinking during chemistry education learning activities on climate change. ***104th Canadian Chemistry Conference and Exhibition*** (Oral, online), August 2021.
6. **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. A pilot study: Investigating how undergraduate chemistry students engage in systems thinking in chemistry education and the impact of collaborative systems thinking tasks. ***Chemistry and Biochemistry Graduate Research Conference*** (Oral, online), Montreal, Québec, November 2021.
7. * **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. Investigating how people (learners and experts) engage in Systems Thinking in Chemistry Education. ***103rd Canadian Chemistry Conference and Exhibition*** (Oral).

Local

1. **Szozda, A. R.;** Lalani, Z.; Behroozi, S.; Mahaffy, P. G.; Flynn, A. B. "Systems thinking encourages a safe space to offer different perspectives and insights": Student perspectives and experiences with individual and collaborative systems thinking activities. **uOttawa-Carleton Science Education Symposium** (Oral), Ottawa, Ontario, May 2024.
2. ** Szozda, A. R. Equipping students with chemistry knowledge and systems thinking skills to navigate 21st century challenges. **Rockin' Research Event: uOttawa Undergraduate Chemistry Club** (Oral), Ottawa, Ontario, November 2023.
3. **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. Investigating how chemists engage in systems thinking in chemistry education. **Ottawa-Carleton Chemistry Institute Day** (Oral, online), Ottawa, Ontario, June 2020.
4. **Szozda, A. R.;** Mahaffy, P. G.; Flynn, A. B. Investigating educators' perspectives toward systems thinking in chemistry education approaches. **University of Ottawa Chemical and Synthetic Biology Day** (Poster), Ottawa, Ontario, October 2020.

List of Abbreviations

ACS	American Chemical Society
COVID-19	Coronavirus 2019
CER	Chemistry Education Research
DBER	Discipline-Based Education Research
EDI	Equity, Diversity, and Inclusion
FDA	Food and Drug Administration
GenAI	Generative Artificial Intelligence
IPT	Information Processing Theory
IRR	Inter-rater reliability
IRB	Institutional review board
IUPAC	International Union of Pure and Applied Chemistry
JCE	Journal of Chemical Education
KCVS	The King's Centre for Visualization in Science
LTM	Long-term memory
NGSS	Next Generation Science Standards
OECD	Organization for Economic Co-operation and Development
PjBL	Project-based learning
PBL	Problem-based learning
RQ	Research Question
STEM	Science, Technology, Engineering, and Mathematics
ST	Systems Thinking
STICE	Systems Thinking in Chemistry Education
SaSTICE	Sustainability and Systems Thinking in Chemistry Education
STCS 2030+	Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond
SOCME	Systems-oriented concept map extension
SSHRC	Social Science and Humanities Research Council
TCSR	Teacher-Centered Systemic Reform
TA	Teaching assistant
UN SDGs	United Nations Sustainable Development Goals
uOttawa	University of Ottawa
WM	Working memory

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Chapter 1: Introduction

The overarching goal of my doctoral research was to provide evidence and gain a better understanding of what systems thinking (ST) looks like in chemistry education, how it may be implemented and assessed in this field, and the supports needed for chemistry educators' enactment of this approach. Before starting this research, very little chemistry education research was published on this approach. While there have been exceptional research efforts on ST over the last five years, there are still many unanswered questions and aspects of ST in chemistry education that need to be explored.

This chapter will provide readers with all the necessary background information required to conduct chemistry education research on ST. The first section walks readers through an overview of the steps necessary to conduct chemistry education research and its importance. The next section starts by defining ST and its associated terminology then provides a detailed literature review on ST in chemistry education and across disciplines. The final sections of the introduction describe the relevant frameworks relevant to my doctoral research. The introduction concludes with an overview of each chapter presented in this thesis

1.1 A growing discipline - Chemistry Education Research

1.1.1 Defining Chemistry Education Research

Our world is encountering unprecedented social, economic, and environmental challenges driven by accelerated globalization and technological developments. Despite these challenges, such circumstances provide new opportunities for human advancement.¹ Science education plays a pivotal role in equipping students with the knowledge, skills, and attitudes for dynamic and emerging careers, as well as understanding and tackling complex problems.¹⁻³ One might ask: how can we prepare students with the knowledge and skills required for jobs of the 21st century? Answering this question can be informed by discipline-based education research (DBER). DBER aims to “develop evidence-based knowledge and practices that improve teaching and learning in the science, technology, engineering, and mathematics (STEM) disciplines”.^{3,4} DBER provides insights into how students understand the concepts, practices, and ways of thinking about STEM and how to design instructional strategies that improve students' conceptual knowledge and attitudes about learning.^{2,3} A 2012 report by the National Research Council provides (1) readers with a comprehensive synthesis on the contributions and future directions of DBER and (2) educators, policy makers, researchers, scholars, decision makers, government agencies,

curriculum developers, research sponsors, and education advocacy groups with recommendations and resources to improve student learning and further develop DBER.³

Chemistry Education Research (CER) is a type of DBER that investigates the learning and teaching of chemistry using a range of qualitative and quantitative methods grounded in chemistry's priorities, worldview, knowledge, and practices.³ CER studies differ from wet lab chemistry because most of the time, research involves human participants rather than working with chemicals.⁵ The depth of chemistry knowledge, methods and principles from educational research, educational psychology, and cognitive science are all essential components for conducting CER.⁵ CER is quite extensive in the areas that have been explored which include: (1) mechanisms by which students construct an understanding of chemistry principles and barriers that impede constructions,⁶⁻⁸ (2) the development of instruments that measure understanding, attitudes, identity, and other affective constructs,⁹⁻¹¹ (3) how evidence about student learning can be incorporated into curriculum design,¹² and (4) how to measure the impact of curriculum transformations.^{5,8,13-15} Educators can use the insights from CER to adopt scholarly methods in their teaching, ultimately improving student involvement, learning, experiences, and outcomes in chemistry and related disciplines.¹⁶

1.1.2 Steps for conducting Chemistry Education Research

CER is concerned with teaching and learning chemistry rather than directly studying chemistry itself; therefore, the theories that guide the research, the experimental methodologies, and data collection instruments differ from those in traditional chemistry research (Figure 1).⁵ However, some components of conducting CER are quite similar to other areas of chemistry research.

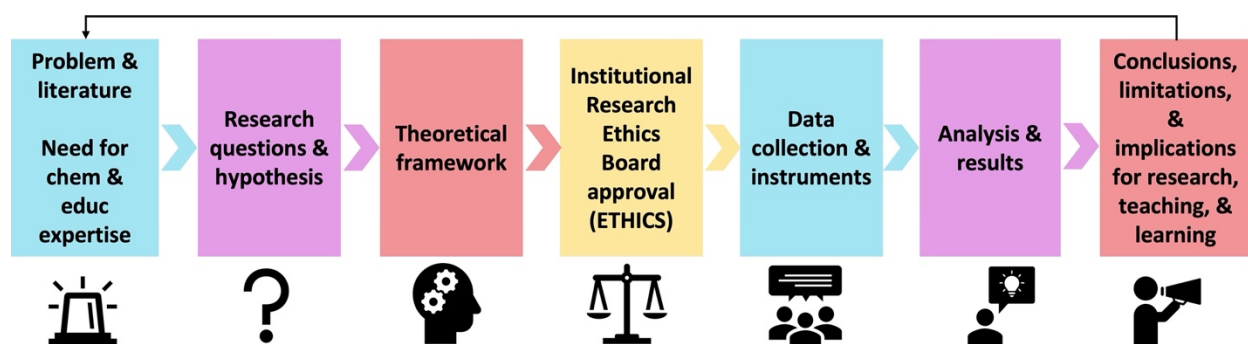


Figure 1. Overview of steps for conducting chemistry education research.

1.1.2.1 Identifying the problem and creating research questions

As with other research areas in chemistry, CER begins with identifying an issue or problem that needs to be resolved and creating research questions that may lead to hypothesis testing, exploratory research,

or other approaches.¹⁶ By defining a problem to investigate, the researcher narrows the scope of the subject matter which can further be defined by generating research questions.¹⁷ Research questions explicitly convey the purpose of completing the research and are integral in guiding the direction of subsequent CER steps of a study which include the study design, data collection, and data analysis. Asking research questions explicitly and intentionally is less common in wet-lab chemistry research because research questions may be assumed based on the type of study. For example, studying reaction mechanisms in solvents with different polarities might explore the effect of polarity on a reaction mechanism. Educational research requires explicit research questions, as studies are often conducted in complex settings. Developing effective and researchable questions can be generated by using a framework. There are several frameworks presented in the literature, but we use one created by Diane Bunce that considers five questions: (1) Is the question worth asking? (2) Is it feasible? (3) Who will be studied? (4) How will it be investigated? and (5) What is the potential “take home” message(s) of the investigation?¹⁸ We used this framework for creating each project of my doctoral research and we revisited the framework to generate new research questions when challenges arose in the research process.

1.1.2.2 Theoretical frameworks

One or more theoretical frameworks guide educational research once the issue is defined and research questions are formulated. A theoretical framework is defined as a “system of ideas, aims, goals, theories and assumptions about knowledge, how research should be carried out, and how research should be reported.”^{16,17,19} Theoretical frameworks are important for influencing interpretive and methodological decisions through the research process.²⁰ Different theoretical frameworks use different approaches for how data is interpreted, which influences methodological decisions, conclusions drawn, and recommendations for researchers and educators.²⁰ In educational research, the same dataset can be analyzed from multiple perspectives to uncover different insights. For example, using a dataset from a study on student performance, one researcher might be interested in investigating how homework completion rates and test scores relate to cognitive load and information processing while another researcher might be interested in exploring how self-efficacy influences student performance. Essentially, we can think of a theoretical framework as a tool to understand and predict phenomena, knowing that there are many ways to describe the same phenomena. Therefore, it is important to critically assess the strengths and limitations of each theoretical framework using criteria such as consistency with data, explanatory and predictive power, and empirical support to identify frameworks that best align with the

research questions and overarching goals.²⁰ Overall, theoretical frameworks are useful for providing a perspective to guide the direction of a study, providing context for the research process, and helping the reader interpret the findings of a study.

1.1.2.3 Institutional Research Ethics Board approval

Ethical practices must be considered throughout the entire research process when the research involves human participants.¹⁷ Educational researchers need to learn about the procedures involved in applying to their institutional research ethics board and adhere to guidelines when developing applications for approval.¹⁷ The Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans has specific guidelines that are based on three core principles: respect for persons, concern for welfare, and justice.²¹ This policy provides an appropriate balance between recognizing the benefits of research, and the protection of participants from research-related harms.²¹ One of the guidelines includes study participants having the right to refuse to participate and withdraw at any time. For these reasons, any research involving human participants must be reviewed by the institutional review board (IRB) and obtain official approval or exemption.¹⁶

1.1.2.4 Data collection and instruments

Quantitative, qualitative, or mixed-method approaches can be used to investigate the research question, once research questions and theoretical frameworks have been established.¹⁷ Qualitative research is best suited to address a research problem where the variables are unknown and can be best learned from participants' perspectives, experiences, and behaviours. Therefore, qualitative research explores "What?", "Why?", and "How?" questions, much like nuclear magnetic resonance experiments can be used to identify a substance or explore reaction mechanisms.¹⁶ Qualitative approaches typically involve smaller sample sizes to explore the depth of a phenomenon and use more open-ended approaches in which the researcher asks general questions of participants, and the participants share the response possibilities.¹⁷ Collecting participants' responses can be done through the use of interviews, observations, focus groups, open-ended responses in questionnaires, and document analysis.¹⁷ Once researchers know the "What?", "Why?", and "How?" of a particular phenomenon, they could design follow-up quantitative studies to see how prevalent the issue is by looking at multiple contexts.

Quantitative research methods aim to answer questions such as "How much?" and "How often?" and these questions are made more specific to obtain measurable and observable data on the variables being investigated.¹⁷ Quantitative approaches generally involve larger sample sizes to explore the

breadth of a phenomenon and use more closed-ended approaches in which the research identifies set response categories (e.g., strongly agree, strongly disagree).¹⁷ Common techniques used to measure the variables in a study include surveys, standardized tests, correlational studies, comparison of two or more groups or data sets, and pre-/post-tests.¹⁷ Data collected through these methods will proceed through statistical analyses that are tailored to the nature of the quantitative data and research objectives (e.g., descriptive, inferential, parametric).¹⁷

Mixed methods use a combination of qualitative and quantitative research methods within a single study or research project.¹⁷ Using a combination of methods, researchers gain a more comprehensive understanding of a phenomenon by drawing on the strength on qualitative and quantitative methods, triangulating findings, and providing richer insights.¹⁷ In a mixed-methods design, researchers can collect and analyze both qualitative and quantitative data, sequentially or concurrently.¹⁷ The benefit of collecting data sequentially is that one approach can generate the findings needed to develop another phase of a study. For example, a researcher could explore the factors that predict students' success in a first-year general chemistry course. Qualitative approaches can be first conducted to understand students' perspectives on what aspects of learning general chemistry are challenging. Then, analyses from the qualitative phase can identify what factors to investigate in the large-scale quantitative phase. While evidence-informed changes are made by having both quantitative and qualitative findings, factors such as availability of resources (e.g., time, funding, equipment, expertise, number of participants) and nature of the research topic may limit what methods can be used.^{16,17} These methods play an important role in gathering evidence for STEM educational approaches.

1.1.2.4.1 Importance of STEM Educational Research

STEM educational research plays an important role in improving citizens' science literacy, making education more inclusive and equitable, and shaping educational policies and practices.²² The National Academies have produced many reports supporting the importance of STEM educational research, yet, the field of research is still undervalued and its importance has long been underemphasized in academia worldwide.^{2,3,23–26} On the other extreme, some educators implement educational approaches based on what they think is the best approach to learning and teaching.^{27,28} Working with intuition without evidence is not efficient, especially when an educators' intuition is incorrect. For example, some educators may tailor their teaching approach to the various learning styles (e.g., visual, auditory, kinesthetic) despite strong evidence showing that adapting teaching to these learning styles does not

improve student learning.^{29–31} Educators need evidence drawn from research to help them implement and justify educational approaches to science teaching and learning.

Educational approaches need evidence for implementation much like the drug approval process (Figure 2). Cooper and Stowe (2018) provide an overview of the nature of evidence in CER studies and describe the strength of conclusions supported by level of evidence.⁵ Here, we draw parallels between STEM educational research and the drug approval process to help different audiences understand the importance for collecting evidence on educational approaches.

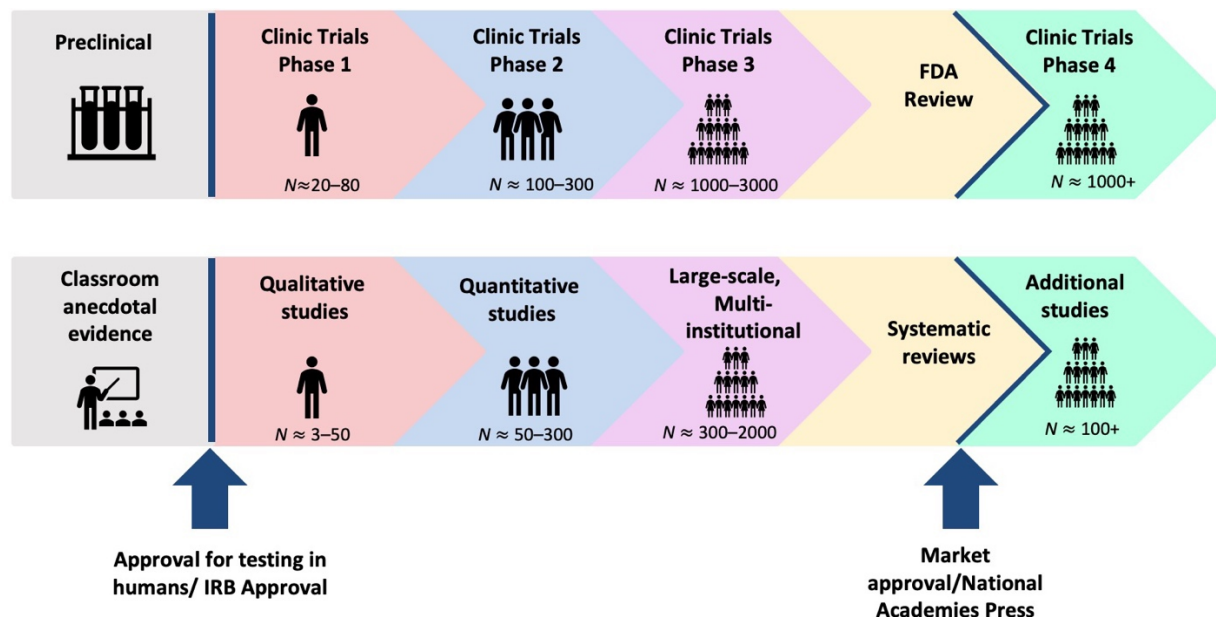


Figure 2. Overview of the parallel between the drug approval process (top) and creating evidence for educational approaches in science educational research (bottom).

A drug must meet preclinical requirements before being used in the market. Meeting preclinical requirements also means that a local institutional review board (IRB) reviews the results from initial in vitro and in vivo studies and decides whether it is reasonably safe for the researchers or company to move forward with testing the drug in humans (e.g., clinical trials).³² The IRB approves the clinical trial protocols, delineating the eligibility criteria for participants, the schedule of tests and procedures, the medications and dosages to be studied, the length of the study and its objective.³² IRBs ensure the study's ethical acceptability, verify participants' informed consent and awareness of associated risks, and that researchers take appropriate steps to protect patients from harm.³²

In STEM educational research, we need IRB approval of our studies to ensure the research meets ethical acceptability before it is carried out with human participants. While research provides benefits for society and for the advancement of knowledge, its undertaking can involve harm (e.g.,

social, behavioral, psychological, physical, or economic) to participants.¹⁷ Therefore, IRB approval of the research is required before the recruitment of participants, formal data collection involving participants, access to data, or collection of human biological materials.³³ Once an educational or clinical study obtains IRB approval, recruitment of participants and data collection can begin.

In Phase 1 of clinical trials, a new drug is tested in a small group of people to determine the most frequent side effects of the drug, how the drug is metabolized and excreted, and most importantly its safety.³² Therefore, Phase 1 does not focus on the generalizability of research findings but on understanding **how** the drug works in the human body and **what** effects the drug produces, similar to qualitative studies in educational research.

Educational research involves conducting qualitative studies with a small number of participants where the goal is to better understand concepts and phenomena of a research problem or when important variables of a topic are unknown.¹⁷ Qualitative research generates rich, detailed data that capture the depth and complexity of human experiences, perceptions, and interactions.¹⁷ To obtain rich data, methods are often limited to a single course or institution, hence generalizability of qualitative research findings is not an expected attribute.¹⁷

Phase 2 of clinical trials aims to obtain data on whether a drug works in people who have a certain disease or condition, requiring a larger sample size (e.g., 100 to 300).³² In Phase 1 of clinical trials, researchers obtained information on how the drug works. Now additional variables need to be investigated to understand for whom the drug benefits and under what conditions. Additionally, a larger sample size is particularly needed for controlled trials where patients receiving the drug are compared with similar patients receiving a different treatment or drug (e.g., placebo, current standard).³²

Similarly, educational research involves conducting quantitative studies which can be informed by qualitative research, enriching the research process and enhancing the depth of understanding about an educational phenomenon.¹⁷ Qualitative exploration can identify the key variables, constructs, or factors that are then quantified and tested in subsequent quantitative research.³⁴ Quantitative studies require a larger sample size to test these variables, constructs, or factors using statistical procedures.³⁴ Expanding the scope of the research through quantitative studies provides more evidence for the effectiveness of an educational intervention, and ultimately enhances the rigour, relevance, and impact of the research.

Phase 3 clinical trial studies gather more evidence of the effectiveness and safety of a drug by studying different populations, different dosages, and using the drug in combination with other drugs.³²

Typically, the number of people involved in these clinical trial studies ranges from 1000 to 3000.³² Phase 3 of clinical trials has a similar goal to multi-institutional studies in DBER.

Educational research can involve follow up multi-institutional or larger scale studies. Multi-institutional research has distinct advantages over single-context studies, including larger sample sizes for more generalizable findings, sharing resources, expertise, and ideas amongst collaborative sites, and promoting networking.^{35–39} Larger sample sizes also enhance the statistical power of analyses, making the generalizability of conclusions stronger.⁴⁰ Generally, teams that conduct multi-institution studies in education or multi-center studies in clinical research can publish in higher impact peer-reviewed journals, leading to more effective dissemination.^{35,37} Therefore, multi-institutional studies can improve the level and quality of evidence of educational approaches since they encompass a broader range of settings and populations; making the findings applicable to a larger audience and more educational contexts.³⁵

Only when there is enough evidence for systematic or FDA review can the drug or educational approach be approved for use in the market. There is no market approval in educational research except in the K-12 system where some aspects may become part of the dictated curriculum. Approaches that have significant evidence may be published in the National Academies Press which publishes authoritative reports issued by The National Academies of Science, Engineering, and Medicine.⁴¹ However, a major issue in education is that intuitive use is common, much like home remedies, naturopathic and homeopathic products. While using intuition can allow for innovation in education, it also has implications for the implementation of evidence-based approaches.^{42–45}

Further studies are conducted even after a drug or educational approach has been marketed. These studies are designed to monitor the effectiveness of the approved intervention in the general population and to collect information about any adverse effects associated with widespread use.

The time required to establish evidence-based educational approaches is extensive, but this process is required to advance science education. With enough evidence, educators can make conclusive decisions about whether a new educational approach benefits students or other stakeholders or creates more harm. We would not administer a drug to a patient if we knew if it was harmful to them. Analogous standards should be considered for implementing educational approaches since education powerfully influences students' careers and life experiences

In addition to collecting evidence of educational research is the need for validity and reliability evidence from the research tools used in the process.

1.1.2.4.2 Collecting validity and reliability evidence

Collecting validity and reliability evidence is an essential component of instrument development in educational research. Validity is defined as “the degree to which evidence and theory support the interpretation of test scores entailed by proposed uses of tests”,^{16,40,46} and reliability is defined as “the consistency of a measure and procedures used to score that measure when it is administered to the same individuals multiple times”.^{16,40,46} Validity and reliability aim to add rigour to a research study by enhancing the credibility and trustworthiness of research findings. Establishing valid (i.e., accurate) and reliable (i.e., precision) data from chemistry instruments is also essential for drawing conclusions and making meaningful interpretations. For example, spectrophotometers are calibrated using standard solutions with known concentrations to ensure accurate measurements of absorbance. Additionally, running replicate samples or conducting control experiments can help assess the reliability of instrument measurements.

For qualitative, quantitative, and mixed-method approaches, instruments are created, or existing instruments are used to collect relevant data for analysis and interpretation. Instruments are research tools designed to measure or assess various constructs, variables, or phenomena relevant to the research questions and goals.¹⁷ The common types of instruments used in educational research include surveys, questionnaires, interview protocols, activities, assessments, and observation guides. The selection and design of appropriate instruments are essential components in conducting research, ensuring that data collection methods align with the research questions and that the instruments provide valid and reliable data.^{5,40} If the data collected from instruments are not valid and reliable, the resulting interpretations will also be invalid and can lead to negative consequences for students and educators.

Qualitative and quantitative research use different approaches for gathering and reporting validity and reliability evidence. In quantitative research, researchers are most concerned about the specific influences made from test scores on psychometric instruments.¹⁷ Validity and reliability in quantitative research can be established through sources of evidence described in the Standards for Educational and Psychological Testing.⁴⁰ Sources of validity evidence include test content, response process, internal structure, and relations to other variations.^{40,46} Whereas, sources of reliability evidence include replicate administrations (e.g., temporal stability) and internal consistency of the instrument. Figure 3 outlines the sources of validity and reliability evidence along with a brief definition and example method for collecting each type of evidence; which are explained in more detail in the Standards for Educational and Psychological Testing.⁴⁰

	Sources of Validity Evidence				Sources of Reliability Evidence	
	Test content	Response process	Internal structure	Relation to other variable	Temporal stability	Internal consistency
Definition of source	Instrument content aligns with intended measure	Instrument engages cognitive processes that are intended by the test developer	Relationship(s) amongst items in the instrument	Correlation between construct of interest and another variable	Instrument consistently measures test-takers' performance on the construct of interest	Different instrument questions consistently measure the same underlying construct
Example of a method	Panel of domain experts	Cognitive interviews with members of target population	Factor analysis to determine factor structure of test	Correlation analysis: correlating test scores with other tests	Test-retest coefficient: test the same group twice	Cronbach's alpha

Figure 3. Overview of sources of validity and reliability evidence with definitions and an example of each method.

In qualitative research, researchers use a lens from the perspective of people who conduct, participate in, or read and review a study, rather than using interpretations from scores and instruments.³⁴ Validity and reliability are often evaluated differently in qualitative research given that data analysis is influenced heavily by the researchers' perspectives.^{17,34} Qualitative researchers need to provide evidence of the trustworthiness of their analysis which can be achieved through a more naturalistic approach proposed by Lincoln and Guba.⁴⁷ The naturalistic approach for establishing trustworthiness consists of four criteria: credibility, transferability, dependability, and confirmability, which are described below.⁴⁷ Procedures for establishing validity in qualitative research include strategies used by researchers to establish the credibility of their study. Credibility is akin to internal structure validity evidence in quantitative research and refers to the degree to which the findings accurately represent the experiences or perspectives of participants.⁴⁷ Several validity procedures can be used to establish trustworthiness in qualitative research including triangulation, member checking, peer debriefing, audit trails, rich description, audit trailing, researcher reflexivity, disconfirming evidence, collaboration, and prolonged engagement in the field.^{34,47} The choice of validity procedures is governed by two perspectives: (1) the lens researchers choose to use (e.g., their own, study participants, or individuals external to the research) to validate their study and (2) researchers' paradigm assumptions or worldviews.^{34,48} Creswell and Miller (2000) created a two-dimensional framework using these perspectives to help researchers identify and provide a rationale for the choice of appropriate validity procedures for their qualitative studies.³⁴

For establishing reliability in qualitative research, some researchers emphasize the need to provide quantitative measures of reliability while others focus on the need to apply Lincoln and Guba's

trustworthiness criteria.^{34,49} Dependability is akin to reliability in quantitative research and refers to the consistency and quality of the research process over time and across researchers.⁴⁹ Dependability can be demonstrated in multiple ways such as peer debriefing, audit trailing, and reflexivity.⁴⁹ For example, audit trailing involves a qualified person outside of a study who will examine the research process from methodological decisions to how the data is used and interpreted, ultimately evaluating the dependability of the findings.^{34,47,49} Conventional approaches for how chemistry education researchers demonstrate the reliability of their analysis are through quantitative inter-rater reliability measures or description of a consensus-making process between multiple researchers.^{49–51} Both of these approaches focus on the construct of reproducibility, capturing the consistency between two or more researchers applying the same codes to the same units of data.^{49,50} Researchers have argued the need to consider reliability when developing a coding scheme (i.e., a guide for labelling data based on codes, rules to apply them, and examples to guide the process) in an analysis and during the final application of the coding scheme.⁴⁹

Inter-rater reliability (IRR) is the most common approach, calculated to indicate the reliability of a finalized coding scheme as applied to the data.^{49,52} In this process, two or more people independently code 10–20% of the data set followed by the primary researcher coding the remaining data. Once the coding is complete, the researchers can use established mathematical approaches to calculate the level of agreement between analyses. A high IRR measure will be obtained when the coding is highly consistent among the raters and researcher, suggesting that the coding scheme is reliable, and the data is being interpreted consistently. Common measurements used for measuring the reliability of data include percent agreement, correlation coefficients (e.g., Pearson's r and intraclass correlation coefficients), and chance-corrected agreement coefficients (e.g., Cohen's kappa and Krippendorff's alpha).^{49,50,53,54} While each of these measurements has pros and cons, the chance-corrected agreement coefficients are suggested to be the most applicable and accepted reliability measures as they adjust simple percent agreement calculations by considering the probability that researchers agree due to chance.^{49,50,54} When researchers do not obtain an acceptable IRR value, the researchers will compare their coding, discuss disagreements, and resolve any discrepancies in their coding. Another cycle of the inter-rater process will be repeated until an acceptable level of agreement is achieved.

In some cases, reliability measures are essential, but in other cases, they can be deemed inappropriate. An example of when gathering evidence for reliability is appropriate would be during the validation of a new assessment tool designed to measure students' cognitive abilities. In this context, reliability is required to ensure the tool can be widely implemented and that it consistently measures

what it is intended to measure. Generally, qualitative, or exploratory research focuses on gaining an in-depth understanding of phenomena rather than obtaining consistent measurements; therefore, reliability may not be a primary focus of the research.

An example where conventional measures of reliability (e.g., inter-rater reliability) may be inappropriate is when exploring the subjective experiences and perspectives of individuals. Personal experiences and perspectives are complex constructs. In studies involving unique or unrepeatable events, such as historical analyses or case studies, reliability may not be applicable since there are no opportunities for repeated measurements. For example, students' experiences of learning chemistry during the COVID-19 pandemic can be highly personal and context-dependent, shaped by factors such as social support networks and cultural or personal beliefs. Another area of chemistry education research where measuring reliability would be inappropriate is qualitative research exploring the experiences of individuals regarding racism and discrimination. Racism and discrimination are complex social phenomena that can manifest in various forms. Therefore, individuals have diverse and multifaceted experiences of racism that are deeply influenced by multiple factors such as their social identities, personal histories, cultural backgrounds, and contextual factors. Researchers prioritize capturing the richness and complexity of these experiences and focus on maximizing the validity and trustworthiness of the findings. In my doctoral research, we collected evidence for different types of validity and reliability based on the goal of each research project.

1.1.2.5 Data analysis

Most data analyses followed established qualitative or quantitative approaches, aligned with the research questions, theoretical framework, and methods.⁵⁵ However, some analyses conducted during my doctoral research did not have established procedures, requiring innovative thinking to devise an analysis plan. We primarily analyzed our data using thematic analysis, a well-established method in qualitative analysis. Thematic analysis is a commonly used qualitative method in educational research, which aims to identify patterns of meaning (themes) within qualitative data.^{17,55–57} Thematic analysis is a versatile and rigorous approach that can be applied to various types of data, such as interviews, focus groups, observations, documents, and open-ended questionnaire responses. Researchers first immerse themselves in the data by reading it and creating memos to become familiar with its content. Researchers then systematically code the data by segmenting it line-by-line into meaningful units known as a code. A code is a word or phrase to represent important concepts or ideas from the data that relate to the research questions.⁵⁶ Coding can be performed deductively, where codes are identified from

existing literature before data analysis begins, or inductively, where codes are formed from the data during analysis.^{17,56} After coding the data, the codes are compared and those that are similar in nature, are grouped into categories. Finally, themes are uncovered from the data by looking for patterns among the categories. Researchers will provide a detailed description of the themes uncovered in a report or manuscript, supported by illustrative quotes or examples from the data or visual representations to illustrate the data in each theme. Overall, thematic analysis allows researchers to gain rich insights into the experiences and perspectives of participants and uncover complex patterns that contribute to the understanding of educational phenomena.^{17,55–57}

1.1.2.6 Conclusions and implications to research, teaching, and learning

CER can range from theoretical exploration to applied research, akin to other areas of chemistry research.¹⁶ Therefore, CER findings can apply to various audiences, informing research, and influencing practice. Researchers must clearly address the relevance of their research to stakeholders (e.g., educators, students, administrators, policymakers, and government agencies) and offer evidence-based suggestions for a meaningful impact of CER.¹⁶ Implications for research, teaching, and learning must remain within the scope of the CER and its findings. Additionally, all studies have limitations which need to be communicated to stakeholders. Limitations may include limited generalizability or applicability based upon design, sampling, subject population, or location of study.¹⁶

Section 1.1 provided an overview of the necessary steps in conducting CER. In the next section, the chapter will narrow in on the specific area of CER conducted in this thesis, systems thinking. Aligned with the steps of CER, this section begins with identifying the overarching problem that we aim to work toward through our ST research.

1.2 Systems Thinking in Chemistry Education and Other Disciplines

1.2.1 Addressing 21st-century challenges

Chemistry has played a central role in creating the material basis of our society and economy; however, projections across a wide range of indicators show that the world is currently on an unsustainable trajectory.^{58–60} Traditional chemistry practices of production and consumption are not sustainable, placing a significant role on current chemistry practices to maximize resource efficiency while minimizing hazards and pollution.⁶¹ Chemists today are faced with a pressing question, “How can we preserve and increase the pace of innovation fundamentally supported and enhanced by the chemical sciences while not adversely affecting human health and the environment?”.⁶² Chemistry has

historically contributed to this unsustainable trajectory; thus chemists today must prioritize tackling complex challenges such as those highlighted by the United Nations' Sustainable Development Goals (SDGs) (Figure 4).⁶³ The 17 SDGs provide a framework for developing a sustainable planetary society by the target date, 2030 and require a holistic understanding of the connections between chemistry and other disciplines.⁵⁸



Figure 4. The 17 United Nations Sustainable Development Goals. Credit: United Nations.⁶³

A transformation of science education is needed to equip citizens and future scientists with the knowledge to understand these complex challenges and be prepared with the skills required to design products that eliminate or minimize harm.⁶⁴ Current approaches in chemistry education often place less emphasis on making connections to other disciplines and global issues. Without practice and assessment, literature on knowledge transfer suggests that students cannot be expected to make these connections.^{65–69} In many chemistry courses, facts are typically learned in silos where emphasis is placed upon detailed descriptions of fundamental, yet narrow, principles.^{61,70,71} While the depth of chemistry is important, learning discrete, unconnected facts out of context limits learners' abilities to apply knowledge and skills in new contexts, such as understanding how chemical processes impact and are impacted by societal, economic, political, and environmental factors.^{61,66,72,71} To advance the SDGs, chemistry education needs a balance between teaching the depth of chemistry knowledge and exploring the breadth of how this knowledge can be applied to new contexts, applicable to the learner and societal and global challenges.

Chemistry educators have also described a disconnect between the demand of preparing students to address global challenges and their knowledge of how to integrate such context and cognitive skills into their chemistry classrooms.^{73–75} Educational systems grapple with the task of equipping students for jobs that are not yet available,⁷⁶ where the ability to adapt, think critically, and solve problems will be in high demand.⁷⁷ 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 employers require.^{78–80} The Organization for Economic Co-operation and Development (OECD) Learning Compass 2030 highlights the importance of cognitive and metacognitive skills, social and emotional skills, and physical and practical skills for 21st-century skills; all these skills are becoming essential as classrooms and workplaces become more diverse and are required for navigating through a complex and uncertain world.⁸¹ Providing opportunities for students to develop and practice these skills and embrace the challenges will set them up for success in their future careers.

Building the capacity to understand and achieve the SDGs and expectations of a 21st-century workplace requires evidence-based approaches to postsecondary STEM education. Recent compelling international calls have been made to reorient chemistry education using a systems thinking (ST) approach.^{65,82} Chemistry educators have proposed ST to complement current teaching approaches to chemistry education that could bridge the disciplines and more effectively educate citizens for their roles on a rapidly changing planet.^{83–87} Students would still learn fundamental chemistry concepts but would develop additional skills to connect chemistry topics to rich contexts such as exploring how a chemical may contribute to intended and unintended consequences.⁸⁸ In support of a ST approach, a broad literature search on the key competencies in sustainability was conducted and synthesized into a coherent framework of a set of five key competencies that guides the design of programs and courses in sustainability, teaching and learning evaluations and hiring and training faculty and staff.^{89,90} The five competencies described through this framework include systems thinking, anticipatory, normative, strategic, and interpersonal competence. Therefore, ST is considered a skill required for jobs of the 21st century and a key competency to be developed in Education for Sustainable Development.

1.2.2 Defining a system and systems thinking

Systems thinking has been a consistent way of thinking, being, and knowing that has existed in many Indigenous communities for many years, long before Western disciplines colonized the term.⁹¹ Indigenous communities are the original systems thinkers that view the natural environment, human relationships, and non-human relationships with a systems lens.⁹² There are unique cultures across Indigenous communities that center many different types of knowledge, referred to as knowledge systems. Members of the Australian Indigenous community, Bundjalung, Thunghutti and Muagal Man Leeton Lee, state, “When we consider knowledge systems from a First Nations perspective, we are looking at many interconnected relationships or pieces of knowledge that overlap and interact with each

other without conflict. This is often referred to as kinship or balance.”⁹² People today continue to use this way of thinking in society to address sustainability challenges.

Western approaches to ST and theories emerged in mid-20th century when recognizing limitations of traditional, reductionist approaches to scientific research.⁹³ Systems have been defined as a “set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviours, often classified as its “function” or “purpose”.⁹⁴ Systems can exist at multiple scales (e.g., microscopic, mesoscopic, and macroscopic), with the observer establishing boundary conditions for a given system.⁸⁶ Our human bodies are an example of a complex system that contain subsystems (e.g., circulatory system, endocrine system, digestive system) with individual parts that work together to keep the body functioning. Systems in biology (e.g., human body, ecosystems), geoscience (e.g., earth systems), engineering (e.g., design systems),⁹⁵ and business (e.g., transaction processing systems, executive information systems),⁹⁶ are perhaps more apparent than chemistry systems (e.g., reaction in a flask, distribution of carbon dioxide in the Earth’s atmosphere) which is why ST approaches have been explored in these fields.^{97–100} However, chemical reactions and processes, in nature and industry, function as parts of complex systems (e.g., global challenges) and interact with other disciplines, giving chemistry the title as the “central science”.⁸⁷ Despite the interconnectedness, ST approaches are relatively unfamiliar to chemists and chemistry educators; therefore, ST has barely been explored in chemistry education.^{61,66,87,101}

Each discipline has a slightly different conception of how to define *systems thinking*. A few examples of these definitions include:

- Systems thinking is “an approach for examining and addressing complex behaviors and phenomena from a more holistic perspective”⁶¹
- Systems thinking is “a school of thought that focuses on recognizing the interconnections between the parts of a system and then synthesizes them into a unified view of the whole. Furthermore, it deals with recognizing patterns and interrelationships, and learning how to structure those interrelationships into more effective, efficient ways of thinking.”^{99,102}
- Systems thinking may be considered a cognitive,⁹⁹ metacognitive,⁹⁸ or higher-order thinking skill,^{99,102,103} and can be developed through appropriate instruction.
- Systems thinking can be viewed as many things: a perspective, a language with its own unique vocabulary, or a toolset for visualizing and communicating.¹⁰⁴

- Systems thinking is a “critical tool in addressing the many environmental, political, social, and economic challenges we face around the world.”⁹⁴
- Systems thinking is a “set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects. These skills work together as a system.”¹⁰⁵

Over the years researchers from different disciplines have suggested ST can be further explained through specific ST skills or cognitive abilities demonstrated by an individual. While there are multiple lists of ST skills in the literature, there is still no consensus about which ST skills should be developed.⁶¹ To interpret these skills, one must understand the ST terminology that is used to define these skills (Table 1).^{94,106}

Table 1. Systems thinking terminology and definitions across disciplines.

Term	Definition
Components	An individual part of a system; can be an attribute of a system, or a subsystem.
Subsystem	A smaller system being embedded within a larger system.
Variables	A type of system component that can be changed/altered.
Behaviour	Specific actions, activities, or responses exhibited by a system’s components. Dynamic behaviours include how a system or system component acts over time.
Function	A distinct purpose, role, or action that a component or subsystem carries out within a larger system. Ultimately, how a part of a system contributes to the overall behaviour and purpose of the entire system.
Relationships	Links between system components. Linear relationship: A constant proportion between cause and effect between two components in a system. Nonlinear relationship: A cause does not produce a proportional effect between two components in a system.
Interconnections/ Interrelated	Links between multiple system components (e.g., more than two components).
Emergent properties/ Emergence	A characteristic of a system that are not just the result of the behaviour of its individual parts. These properties arise from the interactions among the parts and cannot be predicted or explained solely by looking at the parts in isolation.
Feedback	Involves the return of part of the system’s output as input, creating a loop of information or action that can influence the systems’ behaviour. Positive feedback increases the output in response to an increase in input, while negative feedback reduced the output in response to increase in input.
Causal loop/ Feedback loop	A representation of cause-and-effect relationships between variables or components in a system. Causal and feedback loops are often used interchangeably but feedback loops refer to the mechanism through which the outputs of a system are fed back as inputs, influencing the future behaviour of the system.

Unintended consequences	Outcomes that occur unexpectedly or without prior intention due to interconnections and behaviours within a complex system. They are not part of the system's original goal.
Delays	The lengths of time relative to the rates of system changes.
Environment	Refers to the external context or surroundings in which a system exists and interacts. It comprises all the elements that surround and may impact or be impacted by the system. The system and environment are interconnected through feedback loops and relationships, and exchanges of matter, energy, and information.
Boundary	A boundary separates a system from its environment. The borders of the system, determined by the observer(s), which define a particular area of responsibility to achieve system purposes. The decision on where to draw a system's boundary largely depends on the purpose of the discussion or analysis at hand.
Structure	The arrangement of parts within a system and the relationships among them. The structure determines how information flows, how decisions are made, and how actions are taken within a system.

Barry Richmond was the first ST expert to describe seven specific skills involved in ST, in the context of business and management systems.¹⁰⁷ These skills include (1) dynamic thinking, (2) systems-as-cause thinking, (3) forest thinking, (4) operational thinking, (5) closed-loop thinking, (6) quantitative thinking, and (7) scientific thinking (Table 2).^{61,107,108}

Table 2. Comparison of traditional business thinking skills versus systems thinking skills. Adapted from ref 108. Copyright © 2018 Leverage Networks, Inc.

Traditional Business Thinking Skill	Systems Thinking Skill
Static Thinking: Focusing on particular events	Dynamic Thinking: Examining how the behavior of a system changes over time
System-as-Effect Thinking: Viewing behaviour generated by a system as driven by external forces	System-as-Cause Thinking: Considering the internal causes of a systems' behaviour, as opposed to potential external causes of the systems' behaviour
Tree-by-Tree Thinking: Believing that really knowing something requires focusing on the details, which are confined to the behaviours of parts of a system	Forest Thinking: Examining the behaviour of a system as a whole to understand the context of relationships
Factors Thinking: Listing factors that influence or are correlated with some result	Operational Thinking: Focusing on the variables that cause a systems' behaviour and how the variables cause a change in the system's behaviour
Straight-Line Thinking: Viewing causality as running one way, with each cause independent from all other causes	Closed-Loop Thinking: Considering the ways in which two system-relevant variables affect each other, as opposed to how one variable affects the other
Measurement Thinking: Searching for perfectly measured data	Quantitative Thinking: Examining the relative impacts of variables on a given system behaviour, as opposed to the absolute impacts of those variables
Proving-Truth Thinking: Seeking to prove models to be true by validating with historical data	Scientific Thinking: Testing of models and hypotheses about a systems' behaviour

Other researchers across science disciplines suggested that specific ST skills include cognitive abilities such as (1) thinking in terms of dynamic processes (e.g., feedback loops), (2) understanding how the behaviour of a system arises from the interactions of its components over time, (3) discovering and representing feedback processes that underlie observed patterns of the system's behaviour, (4) recognizing delays and understanding their impact, (5) identifying nonlinearities, and (6) scientific thinking.^{97,109} However, these skills are not empirically derived.⁶¹ This limitation began to be addressed in a geoscience study examining the ST abilities of junior high school earth science students.⁹⁹ The researchers found that students engaged in eight ST skills that were developed hierarchically and sequentially (i.e., achievement of lower-level skills is necessary for a student to engage in higher-level skills). This list of skills is now named the Systems Thinking Hierarchical Model, and the eight skills are divided into three components, (1) analysis of system components, (2) synthesis of system components, and (3) implementation (Figure 5).⁹⁹

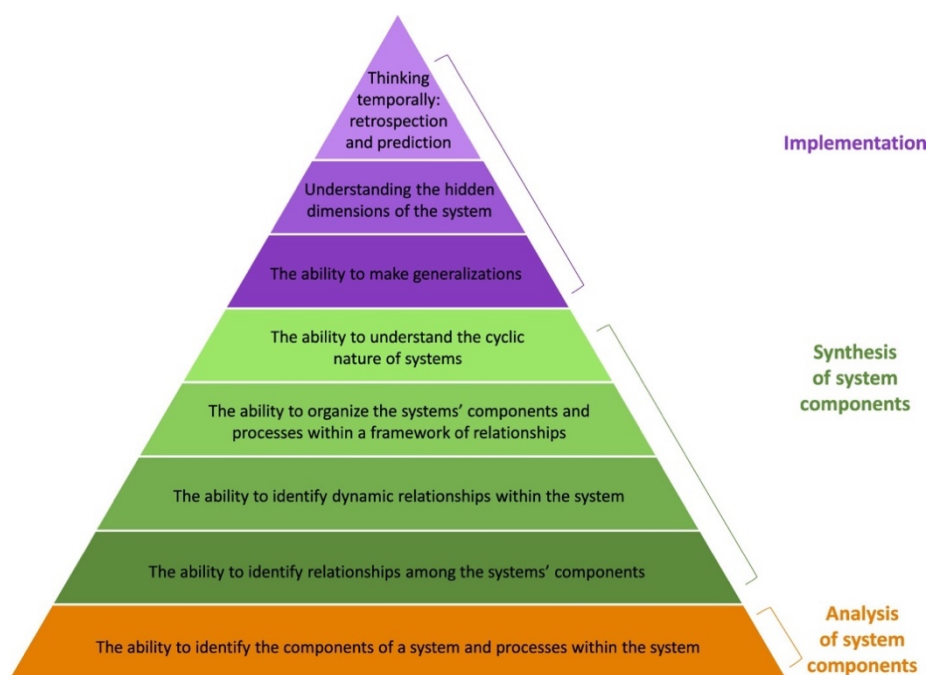


Figure 5. Systems Thinking Hierarchical Model. Reproduced with permission from ref 61. Copyright © 2019 American Chemical Society and Division of Chemical Education, Inc.

This model is relevant to how ST might be applied to chemistry education and has since been used by chemistry educators,^{110,111} however, the research is limited to elementary school students and needs to be explored in the context of chemistry education. For these reasons, chemistry educators have begun defining how ST skills and a ST approach might apply to chemistry education.

1.2.3 Defining systems thinking in chemistry education

The lack of an operational definition of ST remains a challenge for its practical implementation in the chemistry education community. When ST started being introduced to chemistry education, Orgill and York's work helped to define ST in the context of chemistry education.^{61,112} They created five characteristics of a ST in chemistry education by reviewing existing literature about ST in various disciplines and on research about ST teaching and learning. These characteristics are framed in terms of what one should do during an activity that follows a ST approach in chemistry education. After identifying the characteristics, they listed specific ST skills that align with each of the characteristics. These ST skills were organized on an analytical/elaborative-holistic continuum (Table 3). The analytical/elaborative-holistic continuum has roots in systems engineering, educational psychology, and cultural psychology.^{113–115} Additionally, research suggests that deeper learning occurs when students engage in both types of thinking to understand a given concept or phenomenon.^{114,116,117} Therefore, Orgill and York argue that from a cognitive perspective, ST involves analytical skills that focus on parts and holistic skills that focus on wholes and that students would benefit the most from engaging in a ST activity that requires both cognitive processes.¹¹² This work has contributed to defining ST in chemistry education; however, there is no empirical evidence of these characteristics and related ST skills in chemistry education.

Table 3. Five characteristics of ST aligned with ST skills across the analytical-holistic continuum. Figure adapted with permission from ref 109. Copyright © 2020 American Chemical Society and Division of Chemical Education, Inc.

ST characteristics	ST skills		
	Less holistic/more analytical		More holistic/less analytical
 Recognize a system as a whole, not just as a collection of parts	Identify the individual components and processes within a system	Examine the organization of components within the system	Examine a system as a unified whole
 Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviours	Identify the ways in which components of a system are connected	Examine positive and negative feedback loops within a system	Identify and explain the causes of cyclic behaviours within a system
 Identify variables that cause system behaviours, including unique system-level emergent behaviours	Identify the multiple variables that influence a given system-level behaviour; consider the potential effect of stochastic and "hidden" processes on the system-level behaviour	Examine the relative, potentially nonlinear effects that multiple identified variables have on a given system-level behaviour	Identify, examine, and explain emergent system-level behaviours
 Examine how system behaviours change over time	Identify system-level behaviours that change over time	Describe how a given system-level behaviour changes over time	Use system-level behaviour-over-time trends under one set of conditions to make predictions about system-level behaviour-over-time trends under another set of conditions
 Identify interactions between a system and its environment, including the human components of the environment	Identify and describe system boundaries	Consider the possible effects of a system's environment on the system's behaviours; consider how the system under study might be a component of and contribute to the behaviours of a larger system	Consider the role of human actions on current and future system-level behaviors

Some of the terms indicated in the five characteristics of ST are very unfamiliar to those who do not know a lot about ST. Therefore, additional explanations and examples are provided in the following paragraphs.

Feedback loops. Feedback loops include variables that affect the stability of a system. A negative or "balancing" feedback loop reduces the effect of change and helps maintain balance of the system (e.g., Le Chatelier's Principle) whereas as positive or "reinforcing" feedback loop increases the effect of change and produces instability (e.g., autocatalytic reactions). Complex systems often present behaviour in cyclic patterns and these cyclic patterns result from multiple positive and negative feedback loops.

Emergence. Emergence refers to the appearance of properties in a system that arise from the complex interactions between its components. These emergent properties cannot be predicted from the properties of individual parts; instead, new properties emerge from the collective behaviour of the whole, which the individual components do not possess. Common emergent properties exhibited by chemical entities include melting and boiling points, solubility, conductivity, density, acidity, oxidation, and reduction. For example, water is only said to have a density when it is in bulk. Overall, emergent properties provide a new level of explanation by allowing use to describe the behavior of a bulk system in terms of properties like temperature, rather than merely detailing molecular movement. On the other hand, emergent behaviors refer to the patterns or actions that arise from the interactions of components within complex systems arises. These behaviours can be influenced by the interplay of multiple variables and can be influenced by stochastic and hidden processes (e.g., crystallization, enzyme catalysis, micelle formation).

Non-linear relationships. Non-linear relationships exist between causal variables and system-level behaviours or properties. A small disturbance in a system can be amplified nonlinearly, leading to significant effects elsewhere in the system. A common non-linear relationship in enzyme-catalyzed reactions is the Michaelis-Menten mechanism. Enzyme kinetics state that the rate of the reaction does not increase linearly with the concentration of substrate. The non-linear relationship arises because the enzyme becomes saturated with substrate at high concentrations, and adding more substrate does not significantly increase the reaction rate. This behaviour is important in understanding how enzymes function in biological systems and how they can be regulated.

System boundaries. Every system has an artificially defined boundary, and the components outside of this boundary that interact with the system form its environment. In many cases, the system that is defined by the interpreter can be embedded within and become integral components of larger systems. For example, one might need to work across disciplinary boundaries and other systems, including the physical, ecological, and human systems of the plan, as a prerequisite for understanding the relevance of chemistry in addressing different sustainability challenges. Part of creating the boundaries of a system of interest is defining the scope and determining on how much to zoom in and out across granular levels.

Complementing this work, an International Union of Pure and Applied Chemistry (IUPAC) project called Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+) was launched to bring international attention and credibility to catalyze change and increase support for ST in

chemistry education.^{115,116} To date, a working group of the IUPAC STCS 2030+ project informally proposed the following operational definitions of systems-related concepts for implementation in chemistry education that align with Orgill and York's work but are more simplified:¹¹⁹

Systems thinking is the ability to understand and interpret complex problems (ref 120, 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 121, 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:^{114,116–118,122} identifying and examining system components, their organization, causal factors, and system boundaries (analytical), as well as describing and interpreting system-level behaviours, and interactions of the system with its environment (holistic).

This operational definition of systems-related concepts will be useful for maintaining consistency in the implementation, assessment, curriculum development, and research of systems thinking in chemistry education (STICE).

To help illustrate what ST could look like in a chemistry education, consider the following simplified example of using ocean acidification as a topic to introduce concepts of dynamic chemical equilibrium, solubility, and acid–base chemistry in a first-year chemistry course. When atmospheric carbon dioxide (CO_2) dissolves in seawater, it combines with H_2O to form carbonic acid (H_2CO_3) molecules (Figure 6).¹²³ These molecules then dissociate into bicarbonate ions (HCO_3^-) and protons (H^+).¹²³ The protons will readily combine with the available carbonate ions (CO_3^{2-}) to form more bicarbonate ions.¹²³ However, the carbonate ions also react with calcium ions (Ca^{2+}) to form calcium carbonate (CaCO_3), which are required for shells and coral skeletons of marine organisms.¹²³ The solubility of CaCO_3 is dependent on the pH of the seawater.¹²⁴ In alkaline conditions, the precipitation of CaCO_3 will occur spontaneously, while an acidic environment prevents precipitation and supports dissolution.¹²⁴ Therefore, when there are fewer carbonate ions due to increased acidity in the ocean, these organisms have difficulty producing the calcium carbonate required to build these shells, harming aquatic life and disrupting ocean ecosystems.¹²⁴

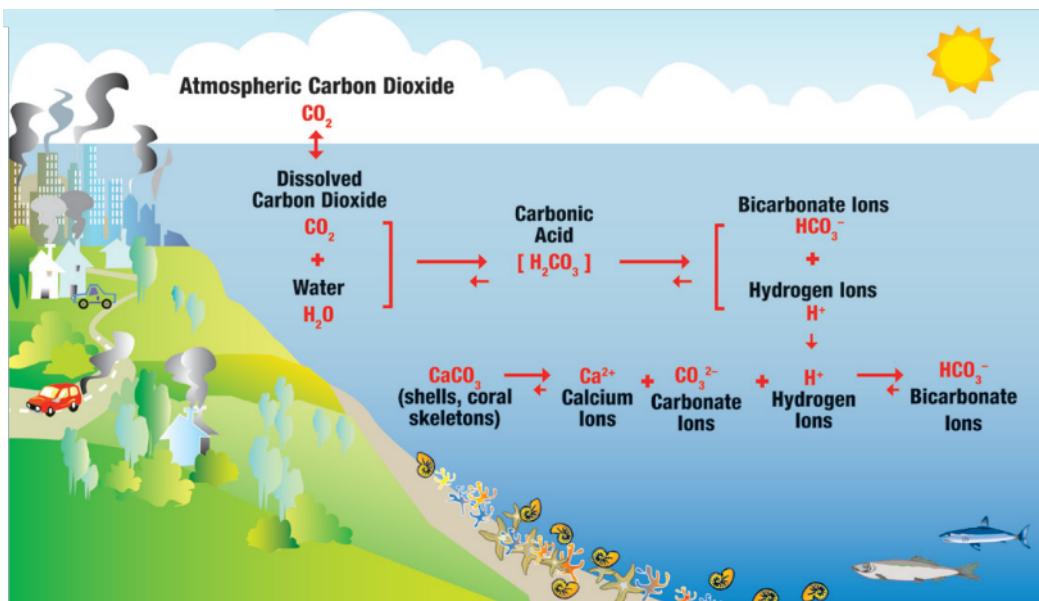


Figure 6. The behaviour of carbon dioxide in sea water. Reproduced from ref. 123.

Many of these steps would typically be presented individually in a first-year chemistry course when introducing the chemical concepts. However, we can view the steps holistically to analyze the interconnections of the chemical concepts and explain how CO_2 in the atmosphere can cause harm to ocean ecosystems. Students would need to consider the dynamic behaviours of the chemicals involved to understand how aquatic organisms are affected by an increase of CO_2 in the atmosphere. The educator could further ask students to think about the variables that could cause an increase and decrease to CO_2 in the atmosphere and how that might change the pH of the ocean and overall effect on aquatic organisms. Carbon dioxide time-series data that is available from the Mauna Loa Observatory in Hawaii can be presented to students to help them identify these relationships and effects.¹²⁵ This example could be further extended by asking students to consider the impacts of ocean acidification on humans. Ocean acidification offers a relevant and interesting context for introducing chemical concepts such as gas and water solubility, chemical equilibrium, and acid-base reactions using a ST approach. Transfer of chemical knowledge to these global challenges, like ocean acidification, is difficult for students and needs to be explicitly taught.^{68,69,126} A ST approach goes beyond providing context to chemistry concepts, it allows the students engage in analytical and holistic thinking to understand the effect of chemicals in global challenges, as shown by this example.

The momentum toward using this approach has also led to important conversations and concerns about (1) how ST is used in chemistry education and (2) how it differs from existing approaches. Chemistry educators commonly think about or use ST as a lens or a tool for teaching and

learning chemistry (pedagogy).^{112,127,128} However, others have used ST to complement the structure and organization of chemistry content within a course (curriculum design/development).^{129,130} Some educators consider ST can be used as both a lens for teaching and learning chemistry and a framework for curriculum design.^{67,85} As this approach continues to be investigated in chemistry education, we will obtain more evidence on how ST should or should not be used in chemistry education.

A few chemistry educators have also identified similarities and differences between a ST approach and existing pedagogical approaches or frameworks to help address educators' confusion on how the approaches are distinct.^{112,128} 3-D learning, context-based approaches, problem-based and project-based learning are most frequently compared with a ST approach in the literature.

Some educators have identified parallels and distinctions of a ST approach and the Next Generation Science Standards (NGSS) crosscutting concepts in the Three Dimensional (3-D) Learning model.^{112,128,131,132} 3-D Learning is designed to help learners move toward more expert ways of understanding and reasoning, built upon three dimensions, (1) disciplinary core ideas, (2) science and engineering practices and (3) crosscutting concepts.¹³¹ Disciplinary core ideas are "the disciplinary-specific concepts that can be used to describe, explain, or understand a wide variety of observations".^{128,131} Science and engineering practices are "the ways in which scientists and engineers use knowledge in investigation and design".^{128,131} Crosscutting concepts "provide lenses through which ideas, phenomena, and observations can be connected and explored across disciplines".^{128,131} Meaningful student learning will occur when all three dimensions are integrated into the curriculum, instruction, and assessment.^{128,131} 3-D Learning was initially intended for K–12 education,¹³³ but the framework has been rapidly gaining attention in postsecondary chemistry education.^{134–137} A ST approach explicitly overlaps with two dimensions of the 3-D model which are, (1) crosscutting concepts and (2) science and engineering practices. ST characteristics and skills align with many of the NGSS crosscutting concepts which include:^{112,128,133}

1. *Systems and System Models*, defining and making models of the system being studied.
2. *Scale, Proportion, and Quantity*, critical elements to consider when building a model of a system or interrogating a system.
3. *Energy and Matter*, tracking two scientifically important quantities into, out of, and within systems.
4. *Stability and Change*, ways of describing how a system functions and evolves with time.

5. *Cause and Effect: Mechanism and Explanation*, investigating and explaining causal relationships and using knowledge of these causes to make predictions about system behaviour.
6. *Patterns*, examining phenomena in terms of patterns in the organization of system components.
7. *Structure and Function*, considering the organization of system components and the properties that emerge from interactions between components.

These crosscutting concepts are described in terms of outcomes rather than empirically derived skills and the description of what constitutes a system is relatively vague, making crosscutting concepts not completely consistent with a ST approach.^{112,128}

The eight science and engineering practices in the 3-D framework include, (1) asking questions and defining problems, (2) developing and using models, (3) planning and carrying out investigations, (4) analyzing and interpreting data, (5) using mathematics and computational thinking, (6) constructing explanations and designing solutions, (7) engaging in argument from evidence, and (8) obtaining, evaluating, and communicating information.¹³³ In general, a ST approach only explicitly aligns with *developing and using models*: “In science, models are used to represent a system (or parts of a system) under study, to aid in the development of questions and explanations, to generate data that can be used to make predictions, and to communicate ideas to others. Students can be expected to evaluate and refine models through an iterative cycle of comparing their predictions with the real world and then adjusting them to gain insights into the phenomenon being modelled. As such, models are based upon evidence. When new evidence is uncovered that the models cannot explain, models are modified.” (ref 138, p. 6). However, this description emphasizes that *developing and using models* connects naturally to other science and engineering practices. Therefore, chemistry educators have emphasized that a learner would likely demonstrate ST skills when engaging in the science and engineering practices concurrently with the crosscutting concepts.¹²⁸

Given this alignment between ST and 3-D Learning, educators may use these terms interchangeably. However, applying ST to chemistry education does not ensure three-dimensionality.¹²⁸ The 3-D Learning framework focuses on a limited number of disciplinary core ideas, as organizing curricula around these core ideas reflects experts’ reasoning with their disciplinary knowledge.^{23,128} However, these core ideas may not be explicit when using a ST approach. Instead, the ideas might be considered hidden/implicit in the depiction of a student.¹²⁸ Pazicni and Flynn (2019) suggest that scaffolded learning activities can help make chemistry core ideas more explicit to better connect

chemistry concepts to human experiences via a ST approach.¹²⁸ Therefore, they claim, “3-D Learning could serve as a valuable framework for instructors who wish to construct systems thinking learning activities or assessments. By combining chemistry core ideas with the cross-cutting concepts and science and engineering practices that leverage Systems Thinking Hierarchy Model skills, instructors can generate systems thinking-based learning performances and, in turn, systems thinking assessments and learning activities.”¹²⁸

Context-based and ST approaches also share similar characteristics, leading to chemistry educators considering them synonymous.¹³⁹ A context-based approach uses real-life examples in a teaching environment in order for students to learn through practical experience with the subject rather than just its theoretical parts.¹⁴⁰ A ST approach can extend a context-based approach where the instructor goes beyond putting a concept in context for students or giving real-world examples in a test or exam question. When using a ST approach, students are the ones who put chemistry concepts in context which goes beyond an observation of facts. Additionally, students use higher-order thinking skills when contextualizing chemistry concepts in a ST approach such as synthesizing and evaluating information, explaining and predicting phenomena and behaviours, and using metacognitive tools.¹⁴¹ While ST and context-based approach share similar characteristics such as contextualization, engagement in other higher-order thinking skills from a ST approach might offer other distinct benefits from context-based learning. Therefore, they should not be considered the same thing. Instead, ST can be used as an additional lens for context-based learning which has been implemented in general chemistry courses.^{142,143}

One paper has also communicated the applicability of ST to project- and problem-based learning approaches. Project- and problem-based learning are both “student-centered learning strategies which aim at fostering deeper learning through active exploration of real-world problems”.¹⁴⁴ In project-based learning (PjBL), educators guide students through an extended inquiry process which includes working collaboratively to develop a product, testing a prototype/plan, and reflecting on the experience.^{144,145} The design principles of PjBL have been linked to applicable ST skills.^{108,144} For example, the design principle, *use of scientific practices*, requires students to construct hypotheses, identify variables, brainstorm, and engaged in problem solving. Identifying variables that cause system-level behaviours is a ST skill that overlaps with this design principle. Similar to PjBL, problem-based learning (PBL) prompts educators to connect chemistry with real-world contexts and allows learners to solve complex problems, independently and collaboratively.^{146,147} Nagarajan and Overton argue that both of these approaches, “contribute to the systems thinking approach by allowing educators to design real-world problems and

projects based on global challenges and engage learners in interdisciplinary learning, thereby empowering them to use the gained knowledge to solve global problems of the 21st century”.¹⁴⁴ The authors give examples of the alignment of Richmond’s seven ST skills to PjBL and PBL in a chemistry education context. However, as previously mentioned, these skills are not empirically derived nor intended for STEM education. Similar to a context-based approach, contextualization of real-world problems is the primary similarity between project- and problem-based learning and ST. A ST approach considers these real-life problems as systems and uses specific skills to understand and analyze them, potentially developing solutions dependent on the goal. Therefore, again, ST can be used as a tool that complements these approaches rather than replacing them.

This section provided an overview of defining systems thinking in chemistry education including its intended uses in the field and comparisons to commonly used teaching methods in chemistry education. The diversity of perspectives of ST approaches to chemistry education is beneficial for exploring the variety of ways ST might be relevant to chemistry education; however, the uncertainty brings challenges to those who would like to implement it in their courses. The goal of this section was to highlight this diversity but also to communicate that educators do not need to start from scratch; ST can be a lens added to existing teaching approaches that may offer additional benefits to student learning in chemistry education.

1.2.4 Limited evidence of the impacts of systems thinking

Some research on ST has been conducted in other disciplines such as Biology, Geoscience, and Engineering,^{100,103,148–154} but there are also a number of articles indicating benefits of ST that are not supported by research evidence.^{72,105,107,155–170} Additionally, most of these papers focus on the use of ST and facilitating student learning through ST principles in K– 12 STEM education as opposed to post-secondary STEM education.^{101,103,150,151,154,160,166,169,171}

Calls to integrate ST approaches in chemistry education have been made based on the proposed benefits of ST from its implementation in other disciplines.^{78,101,112} Since the field of ST is still relatively new to STEM education, the proposed benefits result from a combination of research articles, practitioner articles and theoretical pieces. Claims have been made that ST (1) promotes learning of the chemistry content (*i.e.*, increasing the motivation and engagement of students to learn science,¹⁷¹ increased retention of content,^{156,157} and learning content more deeply and conceptually),^{149,161,162,171–177} (2) develops knowledge and skills needed for reasoning about chemical phenomena (*i.e.*, improving students’ question asking abilities,¹⁷¹ problem solving,¹⁵⁶ and critically thinking skills)¹⁷⁴ and (3) prepares

students to understand and address complex, real-world problems to promote planetary sustainability (*i.e.*, increased abilities to see connections between and within disciplines).^{72,100,120,161,165,166,168,169,171,173,174,177–184}

Overall, rigorous evidence-based research is needed to determine the effects and impacts of ST in chemistry education approaches—emphasizing the importance of our work.⁶⁶

1.2.5 A literature review on systems thinking literature across disciplines.

Despite limited evidence of ST impacts other research on ST can be useful for understanding what we currently know about ST in education and how to guide future research in chemistry education. Several champions have initiated ST research in other STEM disciplines. Assaraf and Orion have published research on ST in earth- and geoscience.^{99,185,185–188} Verhoeff, Boersma, and Waarlo have published ST research in biology.^{98,149,189,190} Hmelo-Silver has worked with several researchers publishing articles on ST in biology and environmental science,^{175,191–194} and Dori, Lavi, and Frank have published some studies related to engineering ST.^{195–203} Most publications in these disciplines focus on the use of ST in K–12 STEM education, as opposed to higher education.¹⁰¹ Additionally, some research articles on ST in biology, environmental science, geoscience, and engineering are somewhat exploratory and have primarily focused on students' development of ST skills.¹⁰¹ The following paragraphs summarize the major findings of ST in these STEM disciplines.

Aligned with cognitive load theory, several studies have reported students have difficulties while working with complex systems (*e.g.*, the human body).^{103,185,186,204,205} For example, secondary students' understanding of biological phenomena tends to focus on macroscopic level features over microscopic (*e.g.*, cellular) level features and they have difficulties understanding and drawing connections between these different levels.^{149,151,185,192,193,206} Additionally, students often find it challenging to identify dynamic relationships that occur within and between a system's various levels.^{185,189} Therefore, connections between the micro and macro levels must be incorporated into teaching and learning processes by explicitly moving back and forth between these levels, rather than teaching them separately.¹⁴⁹ Students also tend to focus on simple linear relationships in systems, and on easily visible components.^{193,207} Similarly, some students think about systems in terms of isolated, static components rather than considering the complex interaction of the components in the system.^{205,208} University students also tend to solve complex systems problems using simplistic arguments.²⁰⁹ However, researchers have indicated that “unlike other types of cognitive activity, systems thinking is not intuitive or innate. When thinking about a problem, we do not naturally think about all things connected to it and their

interrelationships.”²¹⁰ This finding is also commonly present in the literature on problem solving.²¹¹ While students have little experience thinking with and about systems, these findings suggest that ST is not a common way of thinking and the explicit relationships between concepts and dynamic thinking are typically not taught to students.

Students need explicit, scaffolded guidance to help them think systematically and develop ST skills,^{149,152,191,206,212–214} reiterating what we know about how people learn.^{23,24} ST skills must be explicitly taught if they are to be learned rather than through passive engagement in unstructured ST tasks.^{98,99,101} Similarly, learning about systems or ST concepts will not help students develop ST skills. Instead, students need to learn about ST in tandem with actively applying it to specific contexts.¹⁰³ For example, researchers have found that utilizing a combination of innovative learning approaches (e.g., collaborative learning, real-world learning, mobile learning) in authentic environments (e.g., field trips, real-world context) helped foster undergraduate students’ systems thinking competence in an Environmental Studies and Sustainability Development course.²¹⁵ In the context of sustainable competencies, the authors define systems thinking competency as “the ability to recognize the elements in and complexity of a system, to understand the interrelationships of the elements, and to appreciate the impacts of the interrelationships at local, national, and global levels” and state that it cannot be assessed, rather inferred from performance.²¹⁵ Implications from this study suggest that educators should provide learners with overall guidance and allow them to decide the content of knowledge they are supposed to create, collaboratively make sense of the content, and contextualize learning in authentic/real-world cases that involve complex interrelationships.²¹⁵ The *Systems Thinking InTeGrate* instructional module is another example that demonstrates how to scaffold the development of undergraduate students’ ST skills.²¹⁶ This ST module consists of six units that begin with basic terminology and progress to quantitative modelling in the context of sustainability.²¹⁶ After piloting the module in three undergraduate courses (i.e., climate science, environmental science, and oceanography) across three colleges, the researchers found that students who completed the entire module scored significantly higher on ST skills assessments than students who completed only one of the six units.²¹⁶ The module also serves as an open educational resource for educators wanting to implement ST in their courses and addresses efficacy concerns of ST implementation in undergraduate courses.

Researchers also suggest that the ability for students to perceive systems coherently depends on scientific knowledge and cognitive abilities.^{99,205} For example, Kali et al. indicate that understanding more complex systems (e.g., water cycle or carbon cycle) requires engaging in higher-order ST skills (e.g., cyclic and dynamic thinking).¹⁰³ Development of ST skills may also be linked to students’ content

knowledge.^{101,149,188} This finding is emphasized in comparative studies between novices and experts. Experts represent complex systems in terms of interconnected structures, behaviours, and functions, while novices tend to understand systems as isolated structures, showing minimal understanding of the system's function and behaviours.^{192,193} However, with no previous exposure to ST concepts, post-secondary business school students with strong knowledge backgrounds in mathematics and science, showed difficulties with understanding ST concepts, indicating that cognitive inability is not limited to secondary students.¹⁰⁰ While scientific knowledge and cognitive abilities influence students' perceptions of complex systems, there are also a range of tools that have been used to help students visualize the complexity of systems.

One way of teaching complex systems to students is explicitly representing the conceptual framework by using models or concept maps.²¹⁷ A concept is considered a fundamental building block of knowledge.²¹⁸ Students can use concept maps as a way to represent their declarative knowledge structures.¹³² Concept maps are diagrams that generate a visual representation of the relationships between concepts and provide a framework for an individual's ideas for a given topic.^{219,220} Concept maps were developed by Novak to represent the cognitive structures that exist in a learner's mind and can support learners in constructing new knowledge when new information is linked to their prior knowledge.^{219–223} Students' ST skills can be evaluated by tracking the presence and absence of the components in students' models or concept maps.²²¹ One study identified how high school biology students organize their ideas about the human body as a complex system and the ST skills students developed over time by generating concept maps at four strategic points over a 3-year learning process.²²¹ The four concept maps were analyzed qualitatively for each student revealing four learning patterns: (1) structure to process level, (2) macro to micro level, (3) cellular to organism level, and (4) development in complexity of homeostasis mechanisms.²²¹ Conceptual models can also be used to engage in ST and are commonly used in model-based systems engineering.^{132,200} Conceptual models differ from concept maps as they use a formal graphical language where there is a differentiation between several kinds of concepts or entities and a variety of relationships between the concepts or entities (e.g., Object-Process Methodology).^{132,200} However, previous research has shown that students often struggle with developing accurate conceptual models.^{208,224–226} Other work has utilized conceptual modelling with Object-Process Methodology as a way to evaluate the effect of food-related learning units on graduate students' ST and modelling skills and their understanding of STEM issues.¹³² The goal of this research was to raise teachers' ST and scientific understanding skills as the graduate students were prospective teachers.¹³² The researchers found a significant difference between students with

modelling experience and those who were novices, which is supported by previous work that gradual long-term processes are needed to develop these skills.^{132,196,227}

Computer-based learning environments are another method for helping students develop an understanding of systems and their behaviour.^{120,191} Researchers state, “by including assumptions in interactive simulations for instance, the students can test them, and explore the structure, behaviour, and function of system”.^{120,191} This statement was supported by others who argue that “students learn more about system behaviour with dynamic computer models rather than when they create static depictions of system relationships”.^{120,228} Additionally, interactive virtual environments allow students to engage in an authentic scientific practice of using models as tools of observation, exploration, synthesis, and prediction.^{120,228} Studies show that students demonstrate some ST skills when supported in a simulation-based learning environment but still have challenges with understanding and interpreting dynamic behaviours.^{120,228} These studies were conducted with elementary school students suggesting that their scientific knowledge and cognitive abilities might not be fully developed around particular topics, thus requiring gradual engagement with systemic complexity.¹²⁰

Few publications have focused on teachers’ use and implementation of ST approaches in other STEM disciplines.^{229–232} These preliminary investigations indicate that for teachers to facilitate student learning using a ST approach, they need to engage in structured, supported ST activities as learners,^{229,232} receive direct instruction on how to teach ST concepts,²³⁰ and receive ongoing assistance as they integrate these methods into their classroom.²³³

The findings highlighted above bring attention to areas of ST research that have been investigated across disciplines and can be used to guide and inform research on ST in chemistry education.

1.2.6 Initial efforts to infuse systems thinking in chemistry education

Members of the chemistry and chemistry education communities have been promoting a systems approach to highlight the centrality of chemistry in these challenges and guide human action toward sustainability.^{64,67,85,234} However, ST approaches have barely been explored in chemistry education. Therefore, in 2017, the International Union of Pure and Applied Chemistry (IUPAC) launched a global project to infuse Systems Thinking in Chemistry Education (STICE).⁶⁶ The primary goal of this project was to develop learning objectives and strategies to infuse system thinking at the post-secondary level.²³⁵ IUPAC plays a visible role in preparing the global chemistry community for the future; therefore, this initiative was organized as an IUPAC project to bring international attention and credibility to catalyze change, increasing support for STICE. The STICE project outcomes included, (1) reviewing ST approaches

in other STEM fields,¹⁰¹ (2) articulating a framework for STICE,^{66,67} (3) identifying aspects of learning theories relevant to learning ST skills in chemistry,¹²⁸ (4) using ST approaches to integrate green and sustainable chemistry concepts into university-level chemistry classrooms,²³⁶ and (5) identifying considerations for assessing STICE.¹²¹

A few current publications have also challenged the chemistry profession to transform itself by integrating systems thinking in the practice of chemistry to more effectively prepare future citizens and scientists to address current and emerging global challenges.^{58,64,65,71,72,82,237–239} Launching the IUPAC project, along with calls to explore STICE, prompted the request for publications in a Special Issue of the *Journal of Chemistry Education*: “*Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry*”.⁸² This Special Issue was a starting point for STICE, with 43 publications, including: 31 articles,^{61,66,67,101,121,128–130,144,236,240–260} 6 commentaries,^{261–266} 3 laboratory experiments,^{267–269} 2 demonstrations,^{270,271} and 1 teaching activity²⁷² (Figure 7). Of the 31 articles, only 1 research article (CER) was published.

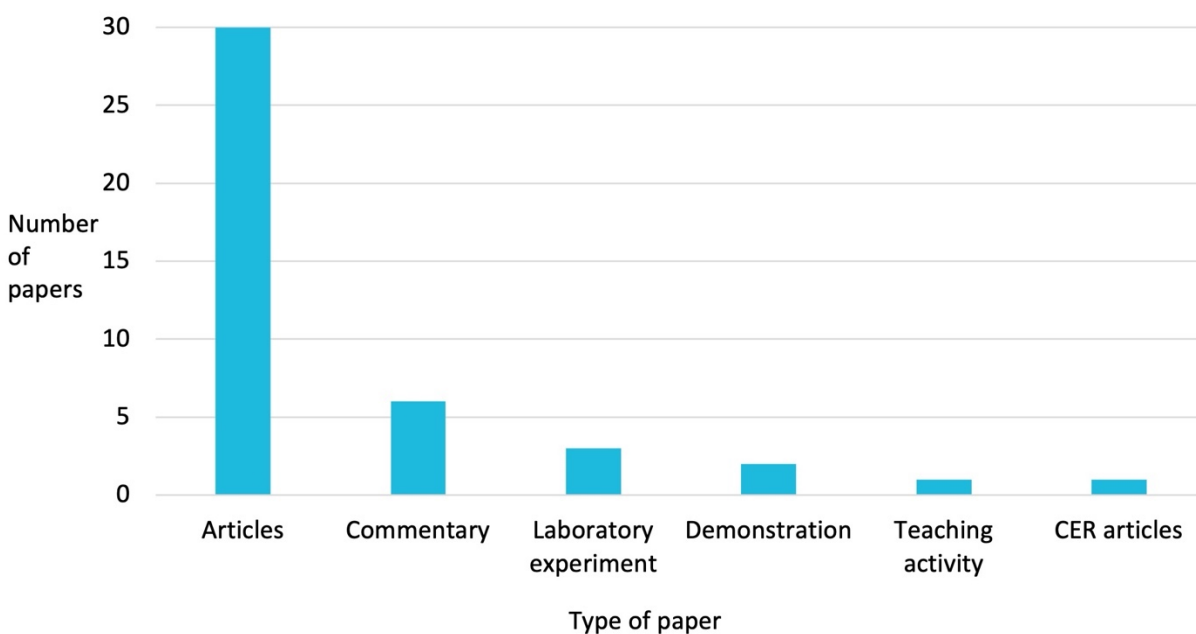


Figure 7. Overview of the papers published in the 2019 Special Issue on ST in the *Journal of Chemical Education*.

Compelling cases were made that:

“All people would benefit from the ability to interpret, explain, and make more informed decisions about issues with deep connections to chemistry, such as those encountered when considering two global sustainability initiatives: the UN Sustainable Development Goals and the Planetary Boundaries Framework.”⁶⁶

The Planetary Boundaries framework provides a quantitative evaluation of nine essential earth systems crucial for sustainable development.^{59,66,274} Additionally, the UN SDGs, outlined in the 2030 Agenda for Sustainable Development and adopted by all UN member states in 2015, serve as a guiding vision for fostering peace and prosperity for both humanity and the planet.^{63,66} Many of the metrics used to measure progress in these global initiatives are based on chemical parameters.^{66,67} Since these frameworks are grounded in the molecular sciences, educators proposed using ST approaches to help draw out the interconnections among chemistry content and features of these two frameworks to help students understand the molecular basis for sustainability.^{67,85} Detailed examples and explanations of connections made between chemical content and each framework were published in *Nature Sustainability* (Figure 8 and Figure 9).⁸⁵



Figure 8. (A) United Nations Sustainable Development Goals Framework. Credit: United Nations.⁶³ (B) Relationship between the global flow of chemical species containing reactive nitrogen and key UN SDGs. Reproduced with permission from ref. 85. Copyright © 2019 Nature Sustainability.

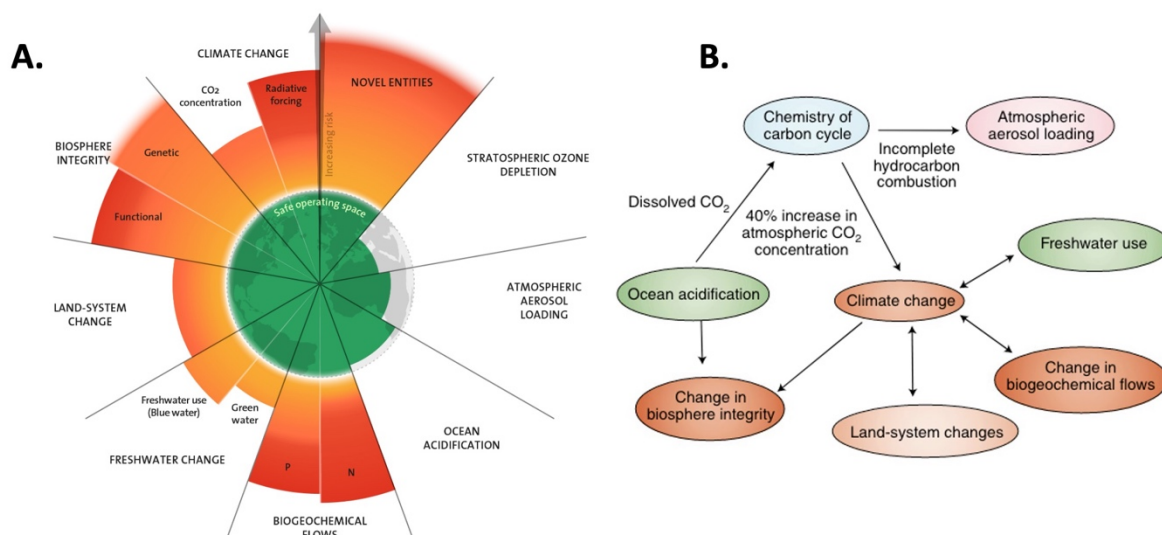


Figure 9. (A) 2023 update to the Planetary Boundaries Framework. Credit: Azote for Stockholm Resilience Centre, based on analysis in Richardson et al 2023.²⁷⁵ (B) Relationships between the planetary carbon cycle and Earth system components in the framework. Reproduced with permission from ref.⁸⁵. Copyright © 2019 Nature Sustainability.

Complementing this work, the authors introduced a new visualization tool called a system-oriented concept map extension (SOCME), to help learners visualize the interconnected concepts when learning about complex systems.^{85,250} Visualizations and other representations such as concept maps have been previously used to support ST and help students navigate the complexity of systems.^{194,250,276,277} However, concept maps are not specifically designed to conceptualize topics in terms of ST.²⁵⁰ SOCMEs differ from concept maps by including the identification of subsystems and their putative boundaries, which is considered a key aspect of defining systems.²⁵⁰ A primary benefit of creating a SOCME is the ability to conceptualize the complexity of systems by breaking the system down into its subsystems, emphasizing the characteristics within chemistry and other science disciplines to define the overall system under consideration.²⁵⁰ The first example of a SOCME was published on the anthropogenic production of CO₂ gas showing its interconnections concepts and topics as it relates to the global carbon cycle (Figure 10).⁸⁵

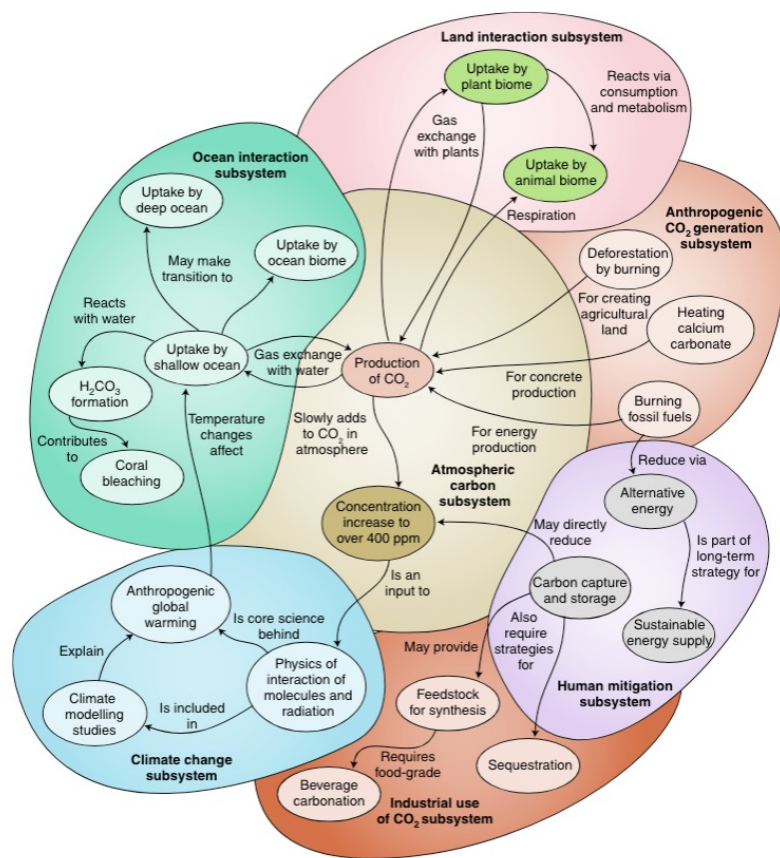


Figure 10. An example of a system-oriented concept map extension (SOCME) on the topic of anthropogenic production of CO₂. Reproduced with permission from ref. 85. Copyright © 2019 Nature Sustainability.

Looking at this example of the anthropogenic production of CO₂, the observer can visualize multiple connections between atmospheric CO₂ and other subsystems of interest.^{85,250} This representation invites students and educators to examine how substances and processes influence each other, how behaviours of the system can change over time, and how a desired outcome can be obtained by altering the quantitative values of elements in the system.⁸⁵ However, not every subsystem needs to be discussed in a course given the intended learning outcomes.⁸⁵ Rather, educators can choose to make some of these connections explicit that align with the intended learning outcomes of a chemistry course, while acknowledging that many others exist— which helps to differentiate a ST approach from a context-based learning approach.⁸⁵ When SOCMEs are not explicitly taught to students engaging in a ST approach, researchers and educators have used the term system maps when students' visual representations do not meet the criteria for a SOCME.²⁷⁸ Therefore, system maps have a broader definition that is more flexible with its criteria including components, connections between the components, and feedback loops.²⁷⁸ The work on SOCMEs and systems maps has been particularly important for demonstrating

ways educators and students can engage with ST approaches in chemistry education; however, assessment of SOCMEs and system maps requires more attention.

1.2.7 Gaps in the literature on systems thinking in chemistry education

Many of ST resources published have made significant contributions to infusing ST in post-secondary chemistry education but linked to the need for educational development efforts is the need for empirical evidence of ST approaches.⁶⁶ Only one article of the 31 articles published was classified as chemistry education research in the Special Issue on STICE which focused on providing some insights and a tool for assessing student understanding from a ST perspective.¹²¹ Therefore, more rigorous, evidence-based research on the effects and impacts of ST approaches in chemistry education is required to determine learners' conceptual understandings and to motivate educators to adopt a ST approach.^{66,82} The need for chemistry education research to investigate and improve ST approaches was also highlighted in a *Future Directions* article written by committee members of the IUPAC project.⁶⁶

Areas of future ST research that are needed include cognitive learning gains, affective domain (feelings), long-term transfer of knowledge and skills, and equity, diversity, and inclusion (EDI) in chemistry.²⁷⁹ Cognitive ST research needs to be conducted to determine how learners' understandings of concepts are influenced by ST approaches to chemistry education. Affective ST research is needed to determine how students feel about chemistry when engaging in ST tasks, as affect is found to be correlated with both academic outcomes and learner engagement,^{280,281} and has been connected to students' gender and racial identity.^{282–284} Approaches to improving EDI must also be explored, as EDI has been lacking in STEM learning and professional environments. This includes the underrepresentation of women and other minority groups in the science profession, which worsens with increased seniority.^{66,285,286} Women's representation in STEM decreases as they progress from high school to post-secondary education, and from there into the labour market.²⁸⁷ The shortage of women in STEM has been widely recognized as detrimental to women, as science and technology occupations are among some of the highest-paying and fastest-growing occupations.²⁸⁷

Students sometimes encounter barriers related to the culture of STEM education along their path to earning a STEM degree such as the shared pattern of norms, behaviours, and values of STEM disciplines.²⁸⁸ The academic environment, including these barriers that students experience in post-secondary education, influences student performance, engagement, and persistence outside of what would be predicted by socioeconomic or academic preparation indicators.²⁸⁸ Therefore, it is important to bring attention to the culture in STEM education as the cultures that students (in particular women and

other underrepresented minority groups) experience shape their awareness and understanding of standards, expectations, and belongings.²⁸⁸ With the ability to connect chemistry and the broader learning environment with experience, culture, and knowledge, students' experiences with ST could have profound influences on feelings of inclusion.^{66,288} In particular, ST approaches could facilitate the engagement of rich conversations that are rarely encountered in the chemistry classroom.⁶⁶

Additionally, while there may be potential benefits and opportunities from implementing STICE, there are also challenges and risks. Educators who choose to implement a ST approach in their course(s) will most likely rely on prepared resources to help them get situated using this approach. However, currently, there is a limited number of high-quality ST teaching resources available and limited methods for assessing or measuring ST competencies.^{66,120,161,289} Additionally, none of these assessment methods have been validated, and they are not designed for easy implementation in large classes, such as first-year university courses.⁶⁶ Beyond individual teaching resources at the course level, there is also a need to integrate STICE in curricula and institutional, national, and international education standards to achieve widespread adoption of STICE.^{250,290,291} However, ST is not the only approach for learning and teaching chemistry concepts, and more research is needed to identify what areas of chemistry are most appropriate for a ST approach.⁶⁶

For ST to be effectively implemented in chemistry education and be beneficial to chemistry learners, we need to identify how willing chemistry educators are to implement ST approaches into their courses, what student, educator, and educational barriers they may face if choosing to adopt a ST approach, and their current perspectives and beliefs towards STICE. These perspectives and beliefs will help researchers identify what CER is needed to improve STICE, and what barriers to STICE are essential to address so that educators are more easily able to enact a ST approach.

1.2.8 Recent initiatives and chemistry education research on systems thinking

Since the release of the Special Issue, there has been an increased effort in chemistry education research and initiatives on STICE aimed to address the gaps in the literature. Some chemistry education research has been published on investigating educators' perspectives of a ST approach and the opportunities and challenges for ST implementation in chemistry education.^{139,242,292–295}

Schultz, Delaney, and Ferguson have published two papers on exploring opportunities and challenges of incorporating ST into secondary and tertiary education.^{292,293} The team conducted a series of exploratory workshops with secondary and tertiary educators and researchers in Australia. In small group semi-structured interviews, they obtained a deeper understanding how these educators and

researchers perceived ST in relation to their teaching and research practice. Multiple perspectives of ST were reported by educators, which includes ST could improve outcomes for: (1) student engagement and motivation by demonstrating the relevance of chemistry to everyday life, (2) student learning by making interdisciplinary connections, (3) empowering students by showing the utilization of chemistry, and (4) perceptions of chemistry by envisaging its benefits. However, preconditions for obtaining these benefits involve overcoming challenges related to curricula (e.g., time and space, assessments) and support (e.g., age-appropriate resources, small classes, and professional learning). Within the same study, the researchers investigated secondary and tertiary educators' and researchers' perspectives of the elements of systems thinking, to measure the amenability of 12 chemistry topics important in both levels of education.²⁸⁹ Three of the 12 topics analyzed (e.g., energy, food chemistry, atmosphere) were rated highly amenable across the five dimensions of ST by both secondary and tertiary participants. Additionally, teaching experience was found to be a key factor in determining an educator's perception of amenability of topics. This work was the first chemistry education research paper to explore educators' perspectives on topics amenable to chemistry education.

Other researchers in the United Kingdom and the United States have also explored tertiary educators' perspectives of systems thinking in chemistry education in different contexts with similar findings. Jackson and Hurst (2021) conducted semi-structured interviews with 14 tertiary chemistry instructors at the University of York,²⁹¹ and York and Orgill (2024) interviewed 17 tertiary chemistry instructors who specifically had experience using ST in various chemistry courses in North America and Europe.²⁹⁵ In addition to the benefits previously reported, York and Orgill found that educators perceive ST to improve courses and teaching practices and a ST approach allows for interdisciplinary collaborations with colleagues.²⁹⁵ This work was one of the first to investigate tertiary educators' perspectives with experience implementing a ST approach, adding to the limited literature on this topic.

Despite the potential opportunities and benefits of ST, all of these studies described above reported some challenges and barriers toward ST implementation which include, time and curriculum constraints,^{290,291,294} concerns with the practicality and suitability of teaching a ST approach,^{293–295} concerns with student workload and resistance,^{294,295} concerns with learning new content and ways of thinking or simply limited knowledge on ST approaches,²⁹⁴ limited instructor resources for teaching a ST approach including assessment tools,²⁹⁴ and ST is challenging to implement due to departmental, institutional, and administrative barriers.²⁹⁴ Given that the use of ST approaches is not widespread, these challenges need to be addressed to better support educators' implementation of ST approaches in chemistry education.

Investigating educators' perspectives on ST was our first contribution to ST research by helping identify what educators need to practically enact a ST in chemistry education, forming the basis of Chapter 2. Our work was also the first article to use an educational change model to help understand the interconnectedness of educator barriers and factors involved and to guide future actions to address educator systemic change.¹³⁹

Other ST research has focused on investigating how students engage with system maps or conceptual modelling in chemistry education, the ST skills they demonstrate,^{110,141} and ways to assess ST.^{110,141,278,296} Chemistry education research conducted by Reynders et al. (2023), Szozda et al. (2023), and Schultz et al. (2022) demonstrated that ST approaches incorporating the use of system map, SOCMEs, or conceptual modelling can be used to engage secondary and post-secondary students in chemistry learning.^{110,141,278} However, developing system maps and SOCMEs takes time and effort for both students and educators. One common finding across all three studies was the difficulty with assessing ST skills, in particular, the development of ST skills through analysis of student-generated system maps.^{110,141,278} Students' system maps are impacted by many factors including students' background knowledge, experiences, beliefs, culture.²⁷⁸ From our work, we recommend using multiple forms of assessment to assess the ST skills showing that students can demonstrate ST skills in multiple ways. Reynders et al. showed that a partial SOCME can be used as a teaching strategy in general chemistry and progress was made to assess the quality and structural complexity students demonstrated by extending the partial SOCME diagram.¹¹⁰ This work shows the potential of implementing and assessing ST approaches in large enrolment courses. Schultz et al. (2022) demonstrated, through multiple vignettes, that secondary students connected sustainability with chemical processes by labelling their system maps with SDGs and positives and negatives.²⁷⁵ Using a different approach from system mapping, Talanquer (2019) assessed general chemistry students chemical ST skills.²⁹⁶ Specifically, a scenario-based assessment was developed to evaluate the extent to which students could apply their understanding of structure-property relationships and thermodynamics in analyzing a realistic problem. The assessment of skills revealed that most students demonstrated sophisticated ways of reasoning based on the analysis of the system under consideration. However, most students demonstrated this skill after significant scaffolding which suggests that the type of mechanistic reasoning that ST demands require time, scaffolding, and multiple opportunities to practice with formative feedback. Overall, progress has been made toward understanding how to implement ST approaches in chemistry using system maps and how to assess ST skills, which resulted in two assessment tools for the chemistry education community to use.^{110,141}

Only a few papers have investigated students' attitudes and perspectives of ST and their experiences with ST activities. Petillion et al. (2019) found students' responses were generally positive towards a revised first-year chemistry curriculum that involved the UN SDGs framework.¹²⁹ Using a ST perspective, the UN SDGs were explicitly linked to the chemistry content using targeted case studies to demonstrate the applicability of introductory chemistry concepts to global challenges.¹²⁹ The student interviews and surveys revealed widespread agreement that the UN SDG case studies provided relevance and societal importance of chemistry and helped maintain student interest and engagement.¹²⁹ Additionally, many students believed the case studies helped them learn the course concepts.¹²⁹ In another study, An et al. (2021) investigated whether a ST instructional approach resulted in changes in students' motivation and attitude levels in general chemistry.²⁹⁷ The results of the study found changes in student motivation to study chemistry were small to negligible and toward lower levels of intrinsic motivation (i.e., engaging in activities to feel pleasure and satisfaction), which align with prior affective studies in chemistry.²⁹⁷ Therefore, the current results do not support the hypothesis that a ST approach will help to induce a differential positive impact on students' intrinsic motivation, relative to more traditional approaches.²⁹⁷ However, the authors postulate a few reasons and study limitations to consider for future studies such as reaching a bigger population, and the "bigger picture" topics used to highlight a ST approach not aligning with universal students' interests. Our work also contributed to understanding students' affective domain (e.g., perspectives) toward ST approaches and was the first to identify the potential impact of collaborative ST approaches toward EDI in chemistry education, described in Chapter 4.⁸⁸ Efforts have also been made to develop ST curricular resources and tools to connect general and organic chemistry topic to ideas of climate,^{111,142,298} global sustainability,⁶⁷ environment and human health,^{236,299,300} and green chemistry.^{301–304} The King's Centre for Visualization in Science (KCVS) has several interactive digital learning tools to support the integration of sustainability and ST into the chemistry curriculum. Planetary Boundaries is one tool created that uses the Planetary Boundaries framework to help educators and learners connect chemistry content to sustainability via ST.^{274,305,306} The tool highlights chemistry's role in regulating individual biophysical Earth system processes and in determining their control variables as well as incorporating aspects of ST such as the dynamic interconnections among the processes and control variables.³⁰⁵ The SOCKit is another interactive, dynamic, digital tool created recently by the KCVS for creating and exploring SOCMEs and facilitating ST.³⁰⁷

A new IUPAC project called Systems Thinking in chemistry for Sustainability: Toward 2030 and Beyond launched in September 2020 from the momentum and success of the previous project, completed in December 2019. This new project guides an interwoven program of work to extend ST into

three strands focused on (1) sustainability, (2) formal chemistry education, and (3) chemical industry.¹⁰⁹ Recently, a working group of this new IUPAC project launched a website disseminating knowledge and resources on Sustainability and Systems Thinking in Chemistry Education (SaSTICE).^{308,309} An educational framework to guide and facilitate the application of ST in the planning, implementation and assessment of chemistry courses was another outcome of the IUPAC project.³¹⁰ This framework is accompanied by examples of the implementation of the framework and their associated educational resources found in the “Systems Thinking in Chemistry Education” sub-website from the IUPAC SaSTICE project, described in more detail in Chapter 6.³¹¹ Other frameworks have also emerged in the literature. Tümay (2023) developed a framework for implementing ST in chemistry education through chemical thinking and meaningful learning in chemistry lens.³¹² Another framework proposed by Talanquer et al. (2020) adopts ST as the underpinning form of reasoning across a core set of competencies along three dimensions (e.g., crosscutting reasoning, core understanding, and fundamental practices) that students should develop to analyze and comprehend complex global systems.³¹³ All three frameworks are beneficial for understanding different perspectives for implementing STICE; however, future research is now needed to collect empirical evidence on the frameworks and to identify any limitations.

1.3 Using change models for implementing systems thinking in chemistry education

Extensive research at the secondary and postsecondary levels has demonstrated the critical role that personal and contextual factors play in educators’ decisions to advance instructional change (i.e., changes in classroom practices used by an individual).^{42,43,314–316} As a result, theoretical support on instructional change has positioned educators at the center of successful educational reform.^{315,316} Additionally, empirical evidence in the literature identifies that beliefs held by an educator about teaching and learning, and their self-efficacy in enacting instructional approaches, influence their adoption of new pedagogy.^{44,318–323} Therefore, characterizing educators’ beliefs, their connection to instructional practices and the factors that influence them are essential to advance instructional change.⁴⁵ Austin (2011) explains many factors impact faculty decision-making about their teaching practice, beginning with the department and discipline, then including the institution and external factors.³²⁴ Overall, understanding instructional change is challenging because many interconnected factors simultaneously influence the individuals involved and the instructional choices that are made.³²⁵

To successfully achieve large-scale transformation, a model of change must be used to take into account all the interconnected pieces that are relevant to the change being made.³²⁵ Change models or theories can be defined as “an analytic construction that describes a generalizable set of observations in

a descriptive and likely predictive sense”.³¹⁷ Therefore, different change models have been proposed depending on the scale of change.

Many scholars have communicated that sustainable educational transformation must be driven by a systems approach.^{317,324,326,327} A systems approach is important for highlighting several aspects of higher education institutions that are critical for understanding how and why change does or does not occur.³²⁴ Some factors can support faculty engagement in research-based teaching approaches, while other factors, at times even the same ones, can serve as hindrances, depending on how they are utilized.³²⁵ For example, if a reward system predominately values research, faculty may feel disincentivized to divert time and energy away from that work.³²⁵ However, if substantial recognition and compensation are tied to specific instructional achievements, then faculty members will interpret this as an indication of the institutional leadership’s priorities.³²⁵

One framework created uses a systems approach to identify and understand barriers to change in STEM teaching practices and to highlight factors and strategies that relate to individual faculty members’ decisions to integrate evidence-based approaches into their teaching practice.³²⁴ This framework highlights: “(1) individual faculty members bring values, backgrounds, abilities, and aspirations to their teaching that relate to the decisions they make; (2) teaching occurs within organizational contexts internal and external to the higher educational organization that influence teaching-related decisions; and (3) several organizational levers are particularly relevant to faculty members’ decision about their teaching”.³²⁴ The interconnections of the levers and barriers in this framework emphasize the dependency of resources on institutional funding which may be increased by prioritizing external research funding.³²⁵ However, such efforts could potentially compromise the quality of the student experience, potentially impacting enrollment, or student success rates and consequently having negative impacts on tuitional based resources.³²⁵ Overall, the complex interrelationships that influence faculty teaching are fundamentally rooted in human relationships and behavioral norms that share the culture within each department, discipline, and institution.³²⁵

The Teacher-Centered Systemic Reform Model, developed by Woodbury and Gess-Newsome (2002), was also created to provide a systemic picture of educational reform and has been empirically developed to highlight the influence of educators’ beliefs on their teaching practices.^{314,318} This model positions educators at the center of educational reform by emphasizing educators’ thinking (i.e., knowledge and beliefs about teaching and learning) and interconnecting their knowledge and beliefs across three domains which are, (1) contextual factors (e.g., broader cultural context, institutional context, department and subject area context, and classroom context), (2) personal factors (e.g., educators’

culture, race, and gender, educators' affect (e.g., motivation, confidence), types and years of teaching experience, nature and extent of educators' preparation to teach, and nature and extent of educators continued learning efforts), and (3) educator experience. The systematic nature of this model highlights the robust link between educators' beliefs and willingness to make changes to their teaching.

We adapted the Teacher-Centered Systemic Reform (TCSR) Model to address the implementation of ST by chemistry educators (Figure 11), which is described in more detail in Chapter 2.^{139,318}

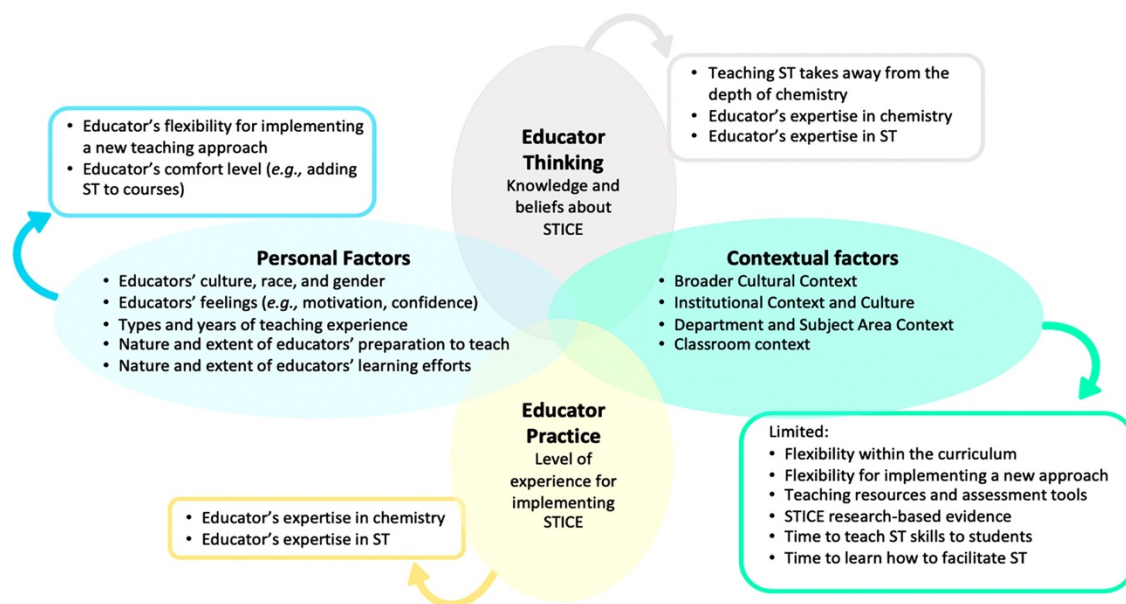


Figure 11. A STICE perspective of the Teacher-Centered Systemic Reform (TCSR) model (opaque ovals), aligned with potential STICE educator and educational barriers (outlined boxes) that we probed in the study. Reproduced with permission from ref. 139. Copyright © 2022 American Chemical Society and Division of Chemical Education, Inc.

For educators to enact a ST approach, educational reform efforts need to consider the interconnectedness between domains in the TCSR model. Using this model can help identify the various contextual levels (e.g., department, institution, professional organizational levels) that may influence an educators' willingness to adopt a STICE approach as well as the individual influences such as self-efficacy, beliefs about teaching and pedagogical training behaviours. We used the four contextual factors in the TCSR, **Broader Cultural Context** (e.g., professional organizations, curricula, teaching resources, research), **Institutional Context** (e.g., size of school and grade levels, community demographics and expectations), **Department and Subject Area Context** (e.g., subject area, department demographics and expectations, educators' class load and schedule), and **Classroom context** (e.g., student demographics, abilities, affect, and personal expectations, teaching resources), since research has identified these factors as prominent barriers to instructional change. Additionally, we aligned each factor with potential STICE educator and

educational barriers. Highlighting the factors brings attention to the increased efforts needed to effectively address these barriers.

Though research on investigating educators' perspectives on ST approaches in chemistry education was published when conducting our study,^{242,292,294,328} our work contributes to a better understanding of educators' perspectives and contexts in order to effectively address their needs.¹³⁹

1.4 Using Information Processing Theory to understand how students engage in systems thinking

We used modern information processing theory (IPT) to guide our research in Chapters 3 and 4 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 in their system maps (Figure 12).^{141,329}

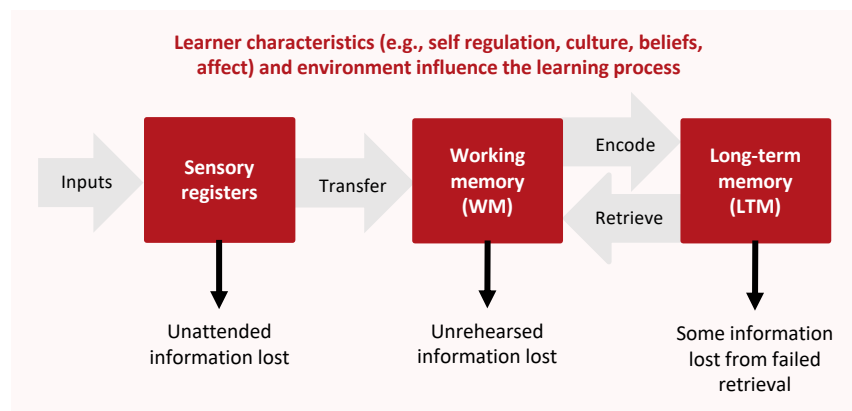


Figure 12. Model of modern information processing theory. Reproduced with permission from ref. 88. Copyright © 2023 American Chemical Society and Division of Chemical Education, Inc.

IPT focuses on how people encode information that is learned and (1) relate it to knowledge in their memory, (2) store new knowledge in their memory, (3) and retrieve the information as needed.³²⁹ Information processing begins when information (e.g., visual, auditory) enters through sensory registers.³³⁰ Information that is perceived useful will enter the working memory (WM), where it is retained through rehearsal and linked with already stored information in the long-term memory (LTM).^{329,331} The WM is a temporary storage space that holds a limited amount of information for a few seconds to minutes whereas the LTM has the capacity to hold information for longer periods (e.g., days, months, years). Information in the WM can be encoded into the LTM, which can be influenced by, elaboration, organization, and link with existing knowledge structures.³³⁰ Encoding refers to the process of converting information into a form that is usable in the brain's storage system. When learners transfer

new information from the WM to LTM, the learner must choose to integrate the new information by perceiving it as meaningful and linking it to their prior knowledge.^{332–334} Doing so, the learner is actively constructing their own knowledge.^{128,335,336} Therefore, to help learners connect new knowledge with existing knowledge and integrate the new knowledge in the LTM is to present the information in a meaningful way and identify and engage with learners' prior knowledge.³³⁷ Modern IPT extended beyond this by incorporating learners' characteristics (i.e., beliefs, self-regulation, culture, and affect) and the learning environment as these factors greatly influence learning.^{128,331} Researchers predict that educators can harness a students' diverse range of prior knowledge in ST approaches beyond just chemistry knowledge.¹²⁸ Each learner can use their prior knowledge to dictate what concepts they consider to be part of a system and what concepts do not.¹²⁸ Therefore, if educators have the goal of effectively activating learners' prior knowledge then strategies must consider learners' experiences, beliefs, and non-content factors (e.g., attitude, cognitive expectations, motivation, self-concept, self-regulatory strategies, understanding the nature of science, etc.). Harnessing some of these non-content factors could affect a learner's ability to demonstrate chemistry knowledge through ST,¹²⁸ as relevant prior knowledge from a learners' long-term memory impacts how that knowledge is stored and organized.¹²

Modern IPT guided the design of a ST intervention described in chapters 3 and 4. We created a ST intervention where the instruction of the tasks followed a progression in which concepts learned build upon each other and effectively integrated learners' prior knowledge. 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.^{88,141} Each student presented this knowledge as a two-dimensional representation (i.e., concept or system map) and created verbal explanations of the knowledge network within each of their minds.³²⁹ 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. We used modern IPT to interpret our findings which led to implications for how to teach ST based on the experiences and perspectives of students engaging in ST tasks.^{88,141}

1.5 Thesis Overview

This is a manuscript-based thesis where each chapter contains a published, peer-reviewed manuscript of the research that I led or that contributed to during my PhD, except Chapter 5, a manuscript in preparation. I start each chapter with a brief introduction of the motivation behind the

work and lessons learned along the way. I draw upon some of the challenges I encountered during my PhD that happened before making academic achievements and I emphasize the importance and value of mentorship that helped me face these challenges. While these aspects are not typically included in a formal PhD thesis, my goal of including these aspects is to (1) challenge the way the academic culture talks about success by communicating the challenges or “failures” of research that are often left out of the conversation and (2) highlight the role that effective mentorship has in graduate school. By doing so, I hope other graduate students can be seen or heard through my personal experiences and help them to believe that they can pursue and achieve a graduate degree despite the challenges.

Chapters 2 to 4 are chemistry education research that I led on ST in collaboration with other members from the Flynn Research Group and Dr. Peter Mahaffy, a collaborator on a Social Sciences and Humanities Research Council (SSHRC) Insight Grant for the ST project. Chapter 5 is a commentary piece for a new ST project I helped develop in our research group and Chapter 6 is collaborative work with Vicente Talanquer as members of the working group for the Systems Thinking in Chemistry for Sustainability: Towards 2030 and Beyond IUPAC project. While Chapter 6 is an external contribution, it deserves a place in this thesis as it complements my work with the Flynn Research Group and has contributed my growth as a researcher in chemistry education. Chapter 7 and 8 conclude this thesis with future directions I believe are needed for STICE research based on the expertise and experience I have obtained over the last five years and a summary of the work I have contributed to the chemistry education community.

1.6 References for Chapter 1

- (1) Organisation for Economic Co-operation and Development. *The Future of Education and Skills: Education 2030*; OECD Publishing: Paris.
- (2) *Reaching Students: What Research Says About Effective Instruction in Undergraduate Science and Engineering*; National Academies Press: Washington, D.C., 2015; p 18687.
<https://doi.org/10.17226/18687>.
- (3) National Research Council. *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*; National Academies Press: Washington, D.C., 2012; p 13362. <https://doi.org/10.17226/13362>.
- (4) Henderson, C.; Connolly, M.; Dolan, E. L.; Finkelstein, N.; Franklin, S.; Malcom, S.; Rasmussen, C.; Redd, K.; St. John, K. Towards the STEM DBER Alliance: Why We Need a Discipline-Based STEM

- Education Research Community. *Int. J. STEM Educ.* **2017**, 4 (1), 14, s40594-017-0076–1. <https://doi.org/10.1186/s40594-017-0076-1>.
- (5) Cooper, M. M.; Stowe, R. L. Chemistry Education Research—From Personal Empiricism to Evidence, Theory, and Informed Practice. *Chem. Rev.* **2018**, 118 (12), 6053–6087. <https://doi.org/10.1021/acs.chemrev.8b00020>.
- (6) Crandell, O. M.; Kouyoumdjian, H.; Underwood, S. M.; Cooper, M. M. Reasoning about Reactions in Organic Chemistry: Starting It in General Chemistry. *J. Chem. Educ.* **2019**, 96 (2), 213–226. <https://doi.org/10.1021/acs.jchemed.8b00784>.
- (7) Keiner, L.; Graulich, N. Transitions between Representational Levels: Characterization of Organic Chemistry Students' Mechanistic Features When Reasoning about Laboratory Work-up Procedures. *Chem. Educ. Res. Pract.* **2020**, 21 (1), 469–482. <https://doi.org/10.1039/C9RP00241C>.
- (8) Flynn, A. B.; Featherstone, R. B. Language of Mechanisms: Exam Analysis Reveals Students' Strengths, Strategies, and Errors When Using the Electron-Pushing Formalism (Curved Arrows) in New Reactions. *Chem. Educ. Res. Pract.* **2017**, 18 (1), 64–77. <https://doi.org/10.1039/C6RP00126B>.
- (9) Xu, X.; Lewis, J. E. Refinement of a Chemistry Attitude Measure for College Students. *J. Chem. Educ.* **2011**, 88 (5), 561–568. <https://doi.org/10.1021/ed900071q>.
- (10) Villafañe, S. M.; Xu, X.; Raker, J. R. Self-Efficacy and Academic Performance in First-Semester Organic Chemistry: Testing a Model of Reciprocal Causation. *Chem. Educ. Res. Pract.* **2016**, 17 (4), 973–984. <https://doi.org/10.1039/C6RP00119J>.
- (11) Raker, J. R.; Gibbons, R. E.; Cruz-Ramírez De Arellano, D. Development and Evaluation of the Organic Chemistry-specific Achievement Emotions Questionnaire (AEQ-OCHEM). *J. Res. Sci. Teach.* **2019**, 56 (2), 163–183. <https://doi.org/10.1002/tea.21474>.
- (12) 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>.
- (13) Tashiro, J.; Talanquer, V. Exploring Inequities in a Traditional and a Reformed General Chemistry Course. *J. Chem. Educ.* **2021**, 98 (12), 3680–3692. <https://doi.org/10.1021/acs.jchemed.1c00821>.
- (14) Underwood, S. M.; Kararo, A. T.; Posey, L. A.; Pollock, A. M.; Herrington, D. G.; Stowe, R. L.; Carmel, J. H.; Klymkowsky, M. W.; Cooper, M. M. Components Critical to Successful Adoption and Adaptation of CLUE, a Transformed General Chemistry Curriculum. *J. Chem. Educ.* **2023**, 100 (9), 3374–3385. <https://doi.org/10.1021/acs.jchemed.3c00190>.

- (15) Cooper, M.; Klymkowsky, M. Chemistry, Life, the Universe, and Everything: A New Approach to General Chemistry, and a Model for Curriculum Reform. *J. Chem. Educ.* **2013**, *90* (9), 1116–1122. <https://doi.org/10.1021/ed300456y>.
- (16) Flynn, A. B. Chemistry Education Research in the *Canadian Journal of Chemistry*: Expanded Scope and Guidelines for Authors. *Can. J. Chem.* **2019**, *97* (10), iii–v. <https://doi.org/10.1139/cjc-2019-0327>.
- (17) Creswell, J. W. *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*; Pearson: Boston, MA, USA, 2012.
- (18) *Nuts and Bolts of Chemical Education Research*; Bunce, D. M., Cole, R. S., Eds.; ACS Symposium Series; American Chemical Society: Washington, DC, 2008; Vol. 976. <https://doi.org/10.1021/bk-2008-0976>.
- (19) Bodner, G. M.; Orgill, M. *Theoretical Frameworks for Research in Chemistry/Science Education*; Prentice Hall series in educational innovation; Pearson/Prentice Hall: Upper Saddle River, NJ, 2007.
- (20) Rodriguez, J.-M. G.; Nardo, J. E.; Finkenstaedt-Quinn, S. A.; Watts, F. M. The Use of Frameworks in Chemistry Education Research. *Chem. Educ. Res. Pract.* **2023**, *24* (4), 1109–1126. <https://doi.org/10.1039/D3RP00149K>.
- (21) Government of Canada. *TCPS 2 (2022) – Chapter 1: Ethics Framework*. https://ethics.gc.ca/eng/tcps2-eptc2_2022_chapter1-chapitre1.html#b (accessed 2024-08-07).
- (22) National Science Teachers Association (NSTA). *NSTA Position Statement: The Role of Research on Science Teaching and Learning*; 2016. https://static.nsta.org/pdfs/PositionStatement_Research.pdf.
- (23) *How People Learn: Brain, Mind, Experience, and School: Expanded Edition*; National Academies Press: Washington, D.C., 2000; p 9853. <https://doi.org/10.17226/9853>.
- (24) Committee on How People Learn II: The Science and Practice of Learning; Board on Behavioral, Cognitive, and Sensory Sciences; Board on Science Education; Division of Behavioral and Social Sciences and Education; National Academies of Sciences, Engineering, and Medicine. *How People Learn II: Learners, Contexts, and Cultures*; National Academies Press: Washington, D.C., 2018; p 24783. <https://doi.org/10.17226/24783>.
- (25) Alberts, B. Why Science Education Is More Important than Most Scientists Think. *FEBS Lett.* **2022**, *596* (2), 149–159. <https://doi.org/10.1002/1873-3468.14272>.

- (26) Kaestle, C. F. The Awful Reputation of Education Research. *Educ. Res.* **1993**, 22 (1), 23.
<https://doi.org/10.2307/1177303>.
- (27) Weinstein, Y.; Smith, M. *Is Intuition the Enemy of Instruction? (Part 2)*.
<https://www.learningscientists.org/blog/2016/2/10/-1> (accessed 2024-05-14).
- (28) Wexler, N. *7 Ways Our Intuition Can Mislead Us About Learning*.
<https://www.forbes.com/sites/nataliewexler/2022/01/03/7-ways-our-intuition-can-mislead-us-about-learning/?sh=700740ee12f1> (accessed 2024-05-14).
- (29) Alley, S.; Plotnikoff, R. C.; Duncan, M. J.; Short, C. E.; Mummery, K.; To, Q. G.; Schoeppe, S.; Rebar, A.; Vandelanotte, C. Does Matching a Personally Tailored Physical Activity Intervention to Participants' Learning Style Improve Intervention Effectiveness and Engagement? *J. Health Psychol.* **2023**, 28 (10), 889–899. <https://doi.org/10.1177/13591053221137184>.
- (30) Cuevas, J. Is Learning Styles-Based Instruction Effective? A Comprehensive Analysis of Recent Research on Learning Styles. *Theory Res. Educ.* **2015**, 13 (3), 308–333.
<https://doi.org/10.1177/1477878515606621>.
- (31) Krätzig, G. P.; Arbuthnott, K. D. Perceptual Learning Style and Learning Proficiency: A Test of the Hypothesis. *J. Educ. Psychol.* **2006**, 98 (1), 238–246. <https://doi.org/10.1037/0022-0663.98.1.238>.
- (32) U.S. Food and Drug Administration. *The FDA's Drug Review Process: Ensuring Drugs Are Safe and Effective*. <https://www.fda.gov/drugs/information-consumers-and-patients-drugs/fdas-drug-review-process-ensuring-drugs-are-safe-and-effective> (accessed 2024-05-10).
- (33) Government of Canada. *Panel on Research Ethics*. https://ethics.gc.ca/eng/tcps2-eptc2_2018_chapter6-chapitre6.html (accessed 2024-05-10).
- (34) 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.
- (35) Cheng, A.; Kessler, D.; Mackinnon, R.; Chang, T. P.; Nadkarni, V. M.; Hunt, E. A.; Duval-Arnould, J.; Lin, Y.; Pusic, M.; Auerbach, M. Conducting Multicenter Research in Healthcare Simulation: Lessons Learned from the INSPIRE Network. *Adv. Simul.* **2017**, 2 (1), 6.
<https://doi.org/10.1186/s41077-017-0039-0>.
- (36) Schwartz, A.; Young, R.; Hicks, P. J.; Appd Learn, F. Medical Education Practice-Based Research Networks: Facilitating Collaborative Research. *Med. Teach.* **2016**, 38 (1), 64–74.
<https://doi.org/10.3109/0142159X.2014.970991>.
- (37) Payne, S.; Seymour, J.; Molassiotis, A.; Froggatt, K.; Grande, G.; Lloyd-Williams, M.; Foster, C.; Wilson, R.; Rolls, L.; Todd, C.; Addington-Hall, J. Benefits and Challenges of Collaborative Research:

- Lessons from Supportive and Palliative Care. *BMJ Support. Palliat. Care* **2011**, 1 (1), 5–11.
<https://doi.org/10.1136/bmjspcare-2011-000018>.
- (38) O’Sullivan, P. S.; Stoddard, H. A.; Kalishman, S. Collaborative Research in Medical Education: A Discussion of Theory and Practice: Collaborative Research in Medical Education. *Med. Educ.* **2010**, 44 (12), 1175–1184. <https://doi.org/10.1111/j.1365-2923.2010.03768.x>.
- (39) Huggett, K. N.; Gusic, M. E.; Greenberg, R.; Ketterer, J. M. Twelve Tips for Conducting Collaborative Research in Medical Education. *Med. Teach.* **2011**, 33 (9), 713–718.
<https://doi.org/10.3109/0142159X.2010.547956>.
- (40) American Educational Research Association; American Psychological Association; National Council on Measurement in Education. *Standards for Educational and Psychological Testing*; American Educational Research Association: Washington, DC, 2014.
- (41) National Academies of Sciences, Engineering, and Medicine. *National Academies Press*.
<https://nap.nationalacademies.org/> (accessed 2024-08-07).
- (42) Lund, T. J.; Stains, M. The Importance of Context: An Exploration of Factors Influencing the Adoption of Student-Centered Teaching among Chemistry, Biology, and Physics Faculty. *Int. J. STEM Educ.* **2015**, 2 (1), 13. <https://doi.org/10.1186/s40594-015-0026-8>.
- (43) Stains, M.; Harshman, J.; Barker, M. K.; Chasteen, S. V.; Cole, R.; DeChenne-Peters, S. E.; Eagan Jr, M. K.; Esson, J. M.; Knight, J. K.; Laski, F. A.; Levis-Fitzgerald, M.; Lee, C. J.; Lo, S. M.; McDonnell, L. M.; McKay, T. A.; Michelotti, N.; Musgrove, A.; Palmer, M. S.; Plank, K. M.; Rodela, T. M.; Sanders, E. R.; Schimpf, N. G.; Schulte, P. M.; Smith, M. K.; Stetzer, M.; Van Valkenburgh, B.; Vinson, E.; Weir, L. K.; Wendel, P. J.; Wheeler, L. B.; Young, A. M. Anatomy of STEM Teaching in North American Universities. *Science* **2018**, 359 (6383), 1468–1470.
<https://doi.org/10.1126/science.aap8892>.
- (44) Gibbons, R. E.; Villafañe, S. M.; Stains, M.; Murphy, K. L.; Raker, J. R. Beliefs about Learning and Enacted Instructional Practices: An Investigation in Postsecondary Chemistry Education. *J. Res. Sci. Teach.* **2018**, 55 (8), 1111–1133. <https://doi.org/10.1002/tea.21444>.
- (45) Popova, M.; Shi, L.; Harshman, J.; Kraft, A.; Stains, M. Untangling a Complex Relationship: Teaching Beliefs and Instructional Practices of Assistant Chemistry Faculty at Research-Intensive Institutions. *Chem. Educ. Res. Pract.* **2020**, 21 (2), 513–527. <https://doi.org/10.1039/c9rp00217k>.
- (46) Arjoon, J. A.; Xu, X.; Lewis, J. E. Understanding the State of the Art for Measurement in Chemistry Education Research: Examining the Psychometric Evidence. *J. Chem. Educ.* **2013**, 90 (5), 536–545.
<https://doi.org/10.1021/ed3002013>.

- (47) Lincoln, Y. S.; Guba, E. G. *Naturalistic Inquiry*; Sage Publications: Beverly Hills, Calif, 1985.
- (48) Guba, E. G.; Lincoln, Y. S. Competing Paradigms in Qualitative Research. *Handb. Qual. Res.* **1994**, 105–117.
- (49) Watts, F. M.; Finkenstaedt-Quinn, S. A. The Current State of Methods for Establishing Reliability in Qualitative Chemistry Education Research Articles. *Chem. Educ. Res. Pract.* **2021**, 22 (3), 565–578. <https://doi.org/10.1039/D1RP00007A>.
- (50) Krippendorff, K. Reliability in Content Analysis: Some Common Misconceptions and Recommendations. *Hum. Commun. Res.* **2004**, 30 (3), 411–433. <https://doi.org/10.1093/hcr/30.3.411>.
- (51) Garrison, D. R.; Cleveland-Innes, M.; Koole, M.; Kappelman, J. Revisiting Methodological Issues in Transcript Analysis: Negotiated Coding and Reliability. *Internet High. Educ.* **2006**, 9 (1), 1–8. <https://doi.org/10.1016/j.iheduc.2005.11.001>.
- (52) Krippendorff, K. *Content Analysis: An Introduction to Its Methodology*, 2nd ed.; Sage: Thousand Oaks, Calif, 2004.
- (53) Neuendorf, K. A. *The Content Analysis Guidebook*; SAGE Publications, Inc: 2455 Teller Road, Thousand Oaks California 91320, 2017. <https://doi.org/10.4135/9781071802878>.
- (54) Cohen, J. A Coefficient of Agreement for Nominal Scales. *Educ. Psychol. Meas.* **1960**, 20 (1), 37–46. <https://doi.org/10.1177/001316446002000104>.
- (55) Boyatzis, R. *Transforming Qualitative Information: Thematic Analysis and Code Development*; SAGE Publications, Inc: Thousand Oaks, California, 1998.
- (56) Saldaña, J. *The Coding Manual for Qualitative Researchers*, 3rd ed.; SAGE Publications, Inc.: Thousand Oaks, California, 2016.
- (57) Braun, V.; Clarke, V. Using Thematic Analysis in Psychology. *Qual. Res. Psychol.* **2006**, 3 (2), 77–101. <https://doi.org/10.1191/1478088706qp063oa>.
- (58) Anastas, P. T.; Zimmerman, J. B. The United Nations Sustainability Goals: How Can Sustainable Chemistry Contribute? *Curr. Opin. Green Sustain. Chem.* **2018**, 13, 150–153. <https://doi.org/10.1016/j.cogsc.2018.04.017>.
- (59) Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S. E.; Fetzer, I.; Bennett, E. M.; Biggs, R.; Carpenter, S. R.; de Vries, W.; de Wit, C. A.; Folke, C.; Gerten, D.; Heinke, J.; Mace, G. M.; Persson, L. M.; Ramanathan, V.; Reyers, B.; Sörlin, S. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, 347 (6223), 1259855. <https://doi.org/10.1126/science.1259855>.

- (60) Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F. S.; Lambin, E. F.; Lenton, T. M.; Scheffer, M.; Folke, C.; Schellnhuber, H. J.; Nykvist, B.; de Wit, C. A.; Hughes, T.; van der Leeuw, S.; Rodhe, H.; Sörlin, S.; Snyder, P. K.; Costanza, R.; Svedin, U.; Falkenmark, M.; Karlberg, L.; Corell, R. W.; Fabry, V. J.; Hansen, J.; Walker, B.; Liverman, D.; Richardson, K.; Crutzen, P.; Foley, J. A. A Safe Operating Space for Humanity. *Nature* **2009**, *461* (7263), 472–475.
<https://doi.org/10.1038/461472a>.
- (61) Orgill, M.; York, S.; MacKellar, J. Introduction to Systems Thinking for the Chemistry Education Community. *J. Chem. Educ.* **2019**, *96* (12), 2720–2729.
<https://doi.org/10.1021/acs.jchemed.9b00169>.
- (62) Anastas, P. T.; Zimmerman, J. B. The Molecular Basis of Sustainability. *Chem* **2016**, *1* (1), 10–12.
<https://doi.org/10.1016/j.chempr.2016.06.016>.
- (63) *United Nations' Sustainable Development Goals*. <http://sustainabledevelopment.un.org/> (accessed 2022-12-16).
- (64) Chemistry Education Needs a Green Reset. *Nature* **2022**, *604* (598).
<https://doi.org/10.1038/d41586-022-01109-z>.
- (65) Mahaffy, P. G.; Krief, A.; Hopf, H.; Mehta, G.; Matlin, S. A. Reorienting Chemistry Education through Systems Thinking. *Nat. Rev. Chem.* **2018**, *2* (4), 126. <https://doi.org/10.1038/s41570-018-0126>.
- (66) 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>.
- (67) 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>.
- (68) Perkins, D. N.; Salomon, G. Knowledge to Go: A Motivational and Dispositional View of Transfer. *Educ. Psychol.* **2012**, *47* (3), 248–258. <https://doi.org/10.1080/00461520.2012.693354>.
- (69) Salomon, G.; Perkins, D. N. Rocky Roads to Transfer: Rethinking Mechanisms of a Neglected Phenomenon. *Educ. Psychol.* **1989**, *24* (2), 113–142.
https://doi.org/10.1207/s15326985ep2402_1.
- (70) Alien, R. T. Reductionism in Education. *Philos. Inq. Educ.* **1991**, *5* (1), 20–35.
<https://doi.org/10.7202/1073354ar>.

- (71) Holme, T. A.; Hutchison, J. E. A Central Learning Outcome for the Central Science. *J. Chem. Educ.* **2018**, *95* (4), 499–501. <https://doi.org/10.1021/acs.jchemed.8b00174>.
- (72) 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>.
- (73) National Research Council. *Assessing 21st Century Skills: Summary of a Workshop*; National Academies Press: Washington, D.C., 2011. <https://doi.org/10.17226/13215>.
- (74) Council, N. R. *Research on Future Skill Demands: A Workshop Summary*; Hilton, M., Ed.; The National Academies Press: Washington, DC, 2008. <https://doi.org/10.17226/12066>.
- (75) National Research Council. *Exploring the Intersection of Science Education and 21st Century Skills: A Workshop Summary*; National Academies Press: Washington, D.C., 2010; p 12771. <https://doi.org/10.17226/12771>.
- (76) Rainie, L.; Anderson, J. *The Future of Jobs and Jobs Training*; Pew Research Center, 2017. <http://www.pewinternet.org/2017/05/03/the-future-of-jobs-and-jobs-training/>.
- (77) 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>.
- (78) 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>.
- (79) 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>.
- (80) 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>.
- (81) Organisation for Economic Co-operation and Development. *OECD Future of Education and Skills 2030*; 2019. https://www.oecd.org/education/2030-project/teaching-and-learning/learning/skills/Skills_for_2030_concept_note.pdf (accessed 2024-03-12).
- (82) 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>.
- (83) 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>.

- (84) 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>.
- (85) 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>.
- (86) Orgill, M.; York, S.; MacKellar, J. Introduction to Systems Thinking for the Chemistry Education Community. *J. Chem. Educ.* **2019**, *96* (12), 2720–2729.
<https://doi.org/10.1021/acs.jchemed.9b00169>.
- (87) 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>.
- (88) Szozda, A. R.; Lalani, Z.; Behroozi, S.; Mahaffy, P. G.; Flynn, A. B. “Systems Thinking (ST) Encourages a Safe Space to Offer Different Perspectives and Insights”: Student Perspectives and Experiences with ST Activities. *J. Chem. Educ.* **2024**, *101* (6), 2290–2307.
<https://doi.org/10.1021/acs.jchemed.4c00080>.
- (89) Redman, A.; Wiek, A. Competencies for Advancing Transformations Towards Sustainability. *Front. Educ.* **2021**, *6*, 785163. <https://doi.org/10.3389/educ.2021.785163>.
- (90) Wiek, A.; Withycombe, L.; Redman, C. L. Key Competencies in Sustainability: A Reference Framework for Academic Program Development. *Sustain. Sci.* **2011**, *6* (2), 203–218.
<https://doi.org/10.1007/s11625-011-0132-6>.
- (91) Goodchild, M. Relational Systems Thinking: That’s How Change Is Going to Come, From Our Earth Mother. *J. Aware.-Based Syst. Change* **2021**, *1* (1), 75–103.
<https://doi.org/10.47061/jabsc.v1i1.577>.
- (92) Glynn-McDonald, R. *First Nations Systems Thinking*.
<https://www.commonground.org.au/article/first-nations-systems-thinking> (accessed 2024-05-09).
- (93) Hammond, D. Philosophical Foundations of Systems Research. In *A Guide to Systems Research*; Edson, M. C., Buckle Henning, P., Sankaran, S., Eds.; Translational Systems Sciences; Springer Singapore: Singapore, 2017; Vol. 10, pp 1–19. https://doi.org/10.1007/978-981-10-0263-2_1.
- (94) Meadows, D. H. *Thinking in Systems: A Primer*; Earthscan: London, 2009.

- (95) Anderson, C.; Cooper, C. *The Engineering for One Planet Framework: Essential Sustainability-Focused Learning Outcomes for Engineering Education*; The Lemelson Foundation: Portland, Oregon, USA, 2022; p 28.
- (96) Florida Tech. *5 Types of Information Systems*.
<https://www.floridatechonline.com/blog/information-technology/5-types-of-information-systems/> (accessed 2024-05-14).
- (97) 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](https://doi.org/10.1002/1520-6858(200033)3:3<163::aid-sys5>3.3.co;2-k).
- (98) 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>.
- (99) 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>.
- (100) Stermann, J. D.; Sweeney, L. B. Bathtub Dynamics: Initial Results of a Systems Thinking Inventory. *Syst. Dyn. Rev.* **2000**, 16 (4), 249–286.
- (101) York, S.; Lavi, R.; Dori, Y. J.; Orgill, M. Applications of Systems Thinking in STEM Education. *J. Chem. Educ.* **2019**, 96 (12), 2742–2751. <https://doi.org/10.1021/acs.jchemed.9b00261>.
- (102) Senge, P. M. *The Fifth Discipline: The Art and Practice of the Learning Organization*, 1. Currency paperback ed.; A Currency Paperback; Currency Doubleday: New York, NY, 1994.
- (103) Kali, Y.; Orion, N.; Eylon, B.-S. Effect of Knowledge Integration Activities on Students' Perception of the Earth's Crust as a Cyclic System. *J. Res. Sci. Teach.* **2003**, 40 (6), 545–565.
<https://doi.org/10.1002/tea.10096>.
- (104) Kim, D. H. *Introduction to Systems Thinking*; Pegasus Communications: Waltham, MA, 1999.
- (105) Arnold, R. D.; Wade, J. P. A Definition of Systems Thinking: A Systems Approach. *Procedia Comput. Sci.* **2015**, 44, 669–678. <https://doi.org/10.1016/j.procs.2015.03.050>.
- (106) Systems Thinking Alliance. *Glossary*. Systems Thinking Alliance.
<https://systemsthinkingalliance.org/glossary/#Causal%20loop> (accessed 2024-05-21).
- (107) Richmond, B. Systems Thinking: Critical Thinking Skills for the 1990s and Beyond. *Syst. Dyn. Rev.* **1993**, 9 (2), 113–133. <https://doi.org/10.1002/sdr.4260090203>.
- (108) Richmond, B. The “Thinking” in Systems Thinking: How Can We Make It Easier to Master? *Syst. Think.* **1997**, 8 (2), 1–5.

- (109) Sweeney, L. B.; Sterman, J. D. Bathtub Dynamics: Initial Results of a Systems Thinking Inventory. *Syst. Dyn. Rev.* **2000**, *16* (4), 249–286. <https://doi.org/10.1002/sdr.198>.
- (110) Reynders, M.; Pilcher, L. A.; Potgieter, M. Teaching and Assessing Systems Thinking in First-Year Chemistry. *J. Chem. Educ.* **2023**, *100* (3), 1357–1365. <https://doi.org/10.1021/acs.jchemed.2c00891>.
- (111) 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>.
- (112) 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>.
- (113) Hitchins, D. K. *Advanced Systems Thinking, Engineering, and Management*; Artech House: Norwood, MA, 2003.
- (114) 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.
- (115) Cheng, H.-Y.; Zhang, S.-Q. Examining the Relationship between Holistic/Analytic Style and Classroom Learning Behaviors of High School Students. *Eur. J. Psychol. Educ.* **2017**, *32* (2), 271–288. <https://doi.org/10.1007/s10212-016-0289-6>.
- (116) 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.
- (117) 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.
- (118) 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>.
- (119) *Systems Thinking in Chemistry for Sustainability: Toward 2030 and beyond (STCS 2030+)*. https://iupac.org/projects/project-details/?project_nr=2020-014-3-050 (accessed 2022-04-06).
- (120) 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>.
- (121) Talanquer, V. Some Insights into Assessing Chemical Systems Thinking. *J. Chem. Educ.* **2019**, *96* (12), 2918–2925. <https://doi.org/10.1021/acs.jchemed.9b00218>.
- (122) Marton, F. Describing and Improving Learning. In *Learning Strategies and Learning Styles*; Springer Science+Business Media: New York, NY, 1988; pp 53–82.
- (123) Gorham, B. *Ocean Acidification: Climate Change's Equally Evil Twin*. <https://socan.eco/ocean-acidification/> (accessed 2024-08-07).
- (124) Hart, P. W.; Colson, G. W.; Burris, J. Application of Carbon Dioxide to Reduce Water Side Lime Scale in Heat Exchanges. *J. Sci. Technol. For. Prod. Process.* **2011**, *1* (2), 67–70.
- (125) National Oceanic and Atmospheric Administration Global Monitoring Laboratory. *Trends in Atmospheric Carbon Dioxide*. <https://gml.noaa.gov/ccgg/trends/> (accessed 2024-08-09).
- (126) Royer, J. M. Theories of the Transfer of Learning. *Educ. Psychol.* **1979**, *14* (1), 53–69.
<https://doi.org/10.1080/00461527909529207>.
- (127) Mahaffy, P. G.; Ho, F. M.; Haack, J. A.; Brush, E. J. Can Chemistry Be a Central Science without Systems Thinking? *J. Chem. Educ.* **2019**, *96* (12), 2679–2681.
<https://doi.org/10.1021/acs.jchemed.9b00991>.
- (128) 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>.
- (129) 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>.
- (130) 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>.
- (131) National Research Council. *Next Generation Science Standards: For States, By States*; National Academies Press: Washington, D.C., 2013; p 18290. <https://doi.org/10.17226/18290>.
- (132) Akiri, E.; Tal, M.; Peretz, R.; Dori, D.; Dori, Y. J. STEM Graduate Students' Systems Thinking, Modeling and Scientific Understanding—The Case of Food Production. *Appl. Sci.* **2020**, *10* (21), 7417. <https://doi.org/10.3390/app10217417>.

- (133) *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; National Academies Press: Washington, D.C., 2012; p 13165. <https://doi.org/10.17226/13165>.
- (134) Cooper, M. M.; Caballero, M. D.; Ebert-May, D.; Fata-Hartley, C. L.; Jardeleza, S. E.; Krajcik, J. S.; Lavery, J. T.; Matz, R. L.; Posey, L. A.; Underwood, S. M. Challenge Faculty to Transform STEM Learning. *Science* **2015**, *350* (6258), 281–282. <https://doi.org/10.1126/science.aab0933>.
- (135) Underwood, S. M.; Posey, L. A.; Herrington, D. G.; Carmel, J. H.; Cooper, M. M. Adapting Assessment Tasks To Support Three-Dimensional Learning. *J. Chem. Educ.* **2018**, *95* (2), 207–217. <https://doi.org/10.1021/acs.jchemed.7b00645>.
- (136) Lavery, J. T.; Underwood, S. M.; Matz, R. L.; Posey, L. A.; Carmel, J. H.; Caballero, M. D.; Fata-Hartley, C. L.; Ebert-May, D.; Jardeleza, S. E.; Cooper, M. M. Characterizing College Science Assessments: The Three-Dimensional Learning Assessment Protocol. *PLOS ONE* **2016**, *11* (9), e0162333. <https://doi.org/10.1371/journal.pone.0162333>.
- (137) Matz, R. L.; Fata-Hartley, C. L.; Posey, L. A.; Lavery, J. T.; Underwood, S. M.; Carmel, J. H.; Herrington, D. G.; Stowe, R. L.; Caballero, M. D.; Ebert-May, D.; Cooper, M. M. Evaluating the Extent of a Large-Scale Transformation in Gateway Science Courses. *Sci. Adv.* **2018**, *4* (10), eaau0554. <https://doi.org/10.1126/sciadv.aau0554>.
- (138) National Academies of Sciences, Engineering, and Medicine. Appendix F: Science and Engineering Practices in the Next Generations Science Standards. In *Next Generation Science Standards: For States, By States*; The National Academies Press: Washington, DC, 2013; p 382.
- (139) 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**, *99* (7), 2474–2483. <https://doi.org/10.1021/acs.jchemed.2c00138>.
- (140) Gilbert, J. K. On the Nature of “Context” in Chemical Education. *Int. J. Sci. Educ.* **2006**, *28* (9), 957–976. <https://doi.org/10.1080/09500690600702470>.
- (141) 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.* **2023**, *100* (5), 1763–1776. <https://doi.org/10.1021/acs.jchemed.2c00955>.
- (142) Mahaffy, P. G.; Holme, T. A.; Martin-Visscher, L.; Martin, B. E.; Versprille, A.; Kirchhoff, M.; McKenzie, L.; Towns, M. Beyond “Inert” Ideas to Teaching General Chemistry from Rich Contexts: Visualizing the Chemistry of Climate Change (VC3). *J. Chem. Educ.* **2017**, *94* (8), 1027–1035. <https://doi.org/10.1021/acs.jchemed.6b01009>.

- (143) Versprille, A.; Zabih, A.; Holme, T. A.; McKenzie, L.; Mahaffy, P.; Martin, B.; Towns, M. Assessing Student Knowledge of Chemistry and Climate Science Concepts Associated with Climate Change: Resources To Inform Teaching and Learning. *J. Chem. Educ.* **2017**, *94* (4), 407–417. <https://doi.org/10.1021/acs.jchemed.6b00759>.
- (144) Nagarajan, S.; Overton, T. Promoting Systems Thinking Using Project- and Problem-Based Learning. *J. Chem. Educ.* **2019**, *96* (12), 2901–2909. <https://doi.org/10.1021/acs.jchemed.9b00358>.
- (145) Blumenfeld, P. C.; Soloway, E.; Marx, R. W.; Krajcik, J. S.; Guzdial, M.; Palincsar, A. Motivating Project-Based Learning: Sustaining the Doing, Supporting the Learning. *Educ. Psychol.* **1991**, *26* (3–4), 369–398. <https://doi.org/10.1080/00461520.1991.9653139>.
- (146) Hmelo-Silver, C. E. Problem-Based Learning: What and How Do Students Learn? *Educ. Psychol. Rev.* **2004**, *16* (3), 235–266. <https://doi.org/10.1023/B:EDPR.0000034022.16470.f3>.
- (147) Overton, T. Context and Problem-Based Learning. *New Dir.* (3), 7–12. <https://doi.org/10.29311/ndtps.v0i3.409>
- (148) Mathews, L. G.; Jones, A.; Szostak, R.; Repko, A. Using Systems Thinking to Improve Interdisciplinary Learning Outcomes: Reflections on a Pilot Study in Land Economics. *Issues Integr. Stud.* **2008**, *26*, 73–104.
- (149) Verhoeff, R. P.; Waarlo, A. J.; Boersma, K. Th. Systems Modelling and the Development of Coherent Understanding of Cell Biology. *Int. J. Sci. Educ.* **2008**, *30* (4), 543–568. <https://doi.org/10.1080/09500690701237780>.
- (150) 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>.
- (151) 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.
- (152) 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>.
- (153) Maani, K. E.; Maharaj, V. Links between Systems Thinking and Complex Decision Making: Systems Thinking and Complex Decision Making. *Syst. Dyn. Rev.* **2004**, *20* (1), 21–48. <https://doi.org/10.1002/sdr.281>.

- (154) Sheehy, N. P.; Wylie, J. W.; McGuinness, C.; Orchard, G. How Children Solve Environmental Problems: Using Computer Simulations to Investigate Systems Thinking. *Environ. Educ. Res.* **2000**, 6 (2), 109–126. <https://doi.org/10.1080/713664675>.
- (155) Zaraza, R. Systems Thinking in the Classroom. Curriculum Technology, **1995**, <http://www.ascd.org/publications/ctq/1995fall/zaraza.html> (accessed 2024-08-09)
- (156) Sweeney, L. B. *How Is This Similar to That? The Skill of Recognizing Parallel Dynamic Structures on Center Stage*. Creative Learning Exchange [Online]. <http://static.clexchange.org/ftp/documents/Research/RS2005-09Homology.pdf> (accessed 2021-07-29).
- (157) Forrester, J. W. System Dynamics as an Organizing Framework for Pre-college Education. *Syst. Dyn. Rev.* **1993**, 9 (2), 183–194. <https://doi.org/10.1002/sdr.4260090207>.
- (158) Draper, F.; Swanson, M. Learner-Directed Systems Education: A Successful Example. *Syst. Dyn. Rev.* **1990**, 6 (2), 209–213. <https://doi.org/10.1002/sdr.4260060206>.
- (159) Lyneis, D. A. *Bringing System Dynamics to a School Near You*. Creative Learning Exchange. **2001**, <https://proceedings.systemdynamics.org/2000/PDFs/lyneis17.pdf> (accessed 2021-07-29).
- (160) Fisher, D. M. “Everybody Thinking Differently”: K-12 Is a Leverage Point: Everybody Thinking Differently: K-12 Is a Leverage Point. *Syst. Dyn. Rev.* **2011**, 27 (4), 394–411. <https://doi.org/10.1002/sdr.473>.
- (161) Sabelli, N. H. Complexity, Technology, Science, and Education. *J. Learn. Sci.* **2006**, 15 (1), 5–9. https://doi.org/10.1207/s15327809jls1501_3.
- (162) Yoon, S. A.; Goh, S. E.; Park, M. Teaching and Learning About Complex Systems in K–12 Science Education: A Review of Empirical Studies 1995–2015. *Rev. Educ. Res.* **2018**, 88 (2), 285–325. <https://doi.org/10.3102/0034654317746090>.
- (163) 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>.
- (164) Goldstone, R. L.; Wilensky, U. Promoting Transfer by Grounding Complex Systems Principles. *J. Learn. Sci.* **2008**, 17 (4), 465–516. <https://doi.org/10.1080/10508400802394898>.
- (165) Jacobson, M. J.; Wilensky, U. Complex Systems in Education: Scientific and Educational Importance and Implications for the Learning Sciences. *J. Learn. Sci.* **2006**, 15 (1), 11–34. https://doi.org/10.1207/s15327809jls1501_4
- (166) Booth Sweeney, L. Learning to Connect the Dots: Developing Children’s Systems Literacy. *Solutions* **2012**, 5 (3), 55–62. <http://static.clexchange.org/ftp/newsletter/CLEEx23.2.pdf>

- (167) Caulfield, C. W.; Maj, S. P. A Case for Systems Thinking and System Dynamics. In *2001 IEEE International Conference on Systems, Man and Cybernetics. e-Systems and e-Man for Cybernetics in Cyberspace (Cat.No.01CH37236)*; IEEE: Tucson, AZ, USA, 2001; Vol. 5, pp 2793–2798. <https://doi.org/10.1109/ICSMC.2001.971932>.
- (168) Cloud, J. P. Some Systems Thinking Concepts for Environmental Educators during the Decade of Education for Sustainable Development. *Appl. Environ. Educ. Commun.* **2005**, 4 (3), 225–228. <https://doi.org/10.1080/15330150591004625>.
- (169) Forrester, J. W. Learning through System Dynamics as Preparation for the 21st Century. *Syst. Dyn. Rev.* **2016**, 32 (3–4), 187–203. <https://doi.org/10.1002/sdr.1571>.
- (170) Jacobson, M. J. Complex Systems and Learning: Empirical Research, Issues, and “Seeing” Scientific Knowledge with New Eyes. In *International Conference for the Learning Sciences*; International Society of the Learning Sciences: Utrecht, Netherlands, 2008; Vol. 3, pp 266–273.
- (171) Lyneis, D. A. Suggestions for Introducing and Sustaining System Dynamics in K-12 Education. In *International System Dynamics Society Conference, Bergen, Norway*; 2000; Vol. 10, pp 1–16.
- (172) Fisher, D. M. Reflections on Teaching System Dynamics Modeling to Secondary School Students for over 20 Years. *Systems* **2018**, 6 (2). <https://doi.org/10.3390/systems6020012>.
- (173) Fisher, D. “Everybody Thinking Differently”: K-12 Is a Leverage Point. *Syst. Dyn. Rev.* **2011**, 27, 394–411. <https://doi.org/10.1002/sdr.473>.
- (174) Mathews, L.; Jones, A.; Szostak, R.; Repko, A. Using Systems Thinking to Improve Interdisciplinary Learning Outcomes: Reflections on a Pilot Study in Land Economics. *Issues Integr. Stud.* **2008**, 26 (26), 73–104.
- (175) 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.
- (176) Kali, Y.; Orion, N.; Eylon, B.-S. Effect of Knowledge Integration Activities on Students’ Perception of the Earth’s Crust as a Cyclic System. *J. Res. Sci. Teach.* **2003**, 40, 545–565. <https://doi.org/10.1002/tea.10096>.
- (177) Mandinach, E.; Cline, H. Systems, Science, and Schools. *Syst. Dyn. Rev.* **2006**, 9, 195–206. <https://doi.org/10.1002/sdr.4260090208>.
- (178) Richmond, B. Systems Thinking: Critical Thinking Skills for the 1990s and Beyond. *Syst. Dyn. Rev.* **1993**, 9 (2), 113–133. <https://doi.org/10.1002/sdr.4260090203>.
- (179) Arnold, R. D.; Wade, J. P. A Definition of Systems Thinking: A Systems Approach. *Procedia Comput. Sci.* **2015**, 44, 669–678. <https://doi.org/10.1016/j.procs.2015.03.050>.

- (180) Sweeney, L.; Sterman, J. Thinking about Systems: Student and Teacher Conceptions of Natural and Social Systems. *Syst. Dyn. Rev.* **2007**, *23*, 285–311. <https://doi.org/10.1002/sdr.366>.
- (181) Jacobson, M. J. Problem Solving, Cognition, and Complex Systems: Differences between Experts and Novices. *Complexity* **2001**, *6* (3), 41–49. <https://doi.org/10.1002/cplx.1027>.
- (182) Maani, K.; Maharaj, V. Links between Systems Thinking and Complex Decision Making. *Syst. Dyn. Rev.* **2004**, *20*, 21–48. <https://doi.org/10.1002/sdr.281>.
- (183) Sheehy, N. P.; Wylie, J. W.; McGuinness, C.; Orchard, G. How Children Solve Environmental Problems: Using Computer Simulations to Investigate Systems Thinking. *Environ. Educ. Res.* **2000**, *6* (2), 109–126. <https://doi.org/10.1080/713664675>.
- (184) Caulfield, C. W.; Maj, S. P. A Case for Systems Thinking and System Dynamics. In *2001 IEEE International Conference on Systems, Man and Cybernetics. e-Systems and e-Man for Cybernetics in Cyberspace (Cat.No.01CH37236)*; 2001; Vol. 5, pp 2793–2798 vol.5. <https://doi.org/10.1109/ICSMC.2001.971932>.
- (185) Assaraf, O. B.-Z.; Dodick, J.; Tripto, J. High School Students' Understanding of the Human Body System. *Res. Sci. Educ.* **2013**, *43* (1), 33–56. <https://doi.org/10.1007/s11165-011-9245-2>.
- (186) Ben-Zvi-Assaraf, O.; Orion, N. Four Case Studies, Six Years Later: Developing System Thinking Skills in Junior High School and Sustaining Them over Time. *J. Res. Sci. Teach.* **2010**, *47* (10), 1253–1280. <https://doi.org/10.1002/tea.20383>.
- (187) Assaraf, O. B.; Orion, N. System Thinking Skills at the Elementary School Level. *J. Res. Sci. Teach.* **2010**, *47* (5), 540–563. <https://doi.org/10.1002/tea.20351>.
- (188) Batzri, O.; Ben Zvi Assaraf, O.; Cohen, C.; Orion, N. Understanding the Earth Systems: Expressions of Dynamic and Cyclic Thinking Among University Students. *J. Sci. Educ. Technol.* **2015**, *24* (6), 761–775. <https://doi.org/10.1007/s10956-015-9562-8>.
- (189) Boersma, K.; Waarlo, A. J.; Klaassen, K. The Feasibility of Systems Thinking in Biology Education. *J. Biol. Educ.* **2011**, *45* (4), 190–197. <https://doi.org/10.1080/00219266.2011.627139>.
- (190) Verhoeff, R. P.; Boersma, K. T.; Waarlo, A. J. Multiple Representations in Modeling Strategies for the Development of Systems Thinking in Biology Education. In *Multiple Representations in Biological Education*; Treagust, D. F., Tsui, C.-Y., Eds.; Springer Netherlands: Dordrecht, 2013; pp 331–348. https://doi.org/10.1007/978-94-007-4192-8_18.
- (191) Hmelo-Silver, C. E.; Azevedo, R. Understanding Complex Systems: Some Core Challenges. *J. Learn. Sci.* **2006**, *15* (1), 53–61. https://doi.org/10.1207/s15327809jls1501_7.

- (192) Hmelo-Silver, C. E.; Pfeffer, M. G. Comparing Expert and Novice Understanding of a Complex System from the Perspective of Structures, Behaviors, and Functions. *Cogn. Sci.* **2004**, *28* (1), 127–138. https://doi.org/10.1207/s15516709cog2801_7.
- (193) Hmelo-Silver, C. E.; Marathe, S.; Liu, L. Fish Swim, Rocks Sit, and Lungs Breathe: Expert-Novice Understanding of Complex Systems. *J. Learn. Sci.* **2007**, *16* (3), 307–331. <https://doi.org/10.1080/10508400701413401>.
- (194) Hmelo-Silver, C. E.; Jordan, R.; Eberbach, C.; Sinha, S. Systems Learning with a Conceptual Representation: A Quasi-Experimental Study. *Instr. Sci.* **2017**, *45* (1), 53–72. <https://doi.org/10.1007/s11251-016-9392-y>.
- (195) 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>3.0.CO;2-T](https://doi.org/10.1002/1520-6858(200033)3:3<163::AID-SYS5>3.0.CO;2-T).
- (196) Frank, M. Knowledge, Abilities, Cognitive Characteristics and Behavioral Competences of Engineers with High Capacity for Engineering Systems Thinking (CEST). *Syst. Eng.* **2006**, *9* (2), 91–103. <https://doi.org/10.1002/sys.20048>.
- (197) Frank, M. Engineering Systems Thinking: Cognitive Competencies of Successful Systems Engineers. *Procedia Comput. Sci.* **2012**, *8*, 273–278. <https://doi.org/10.1016/j.procs.2012.01.057>.
- (198) Frank, M. What Is “Engineering Systems Thinking”? *Kybernetes* **2002**, *31* (10), 1350–1360. <https://doi.org/10.1108/03684920210443554>.
- (199) Frank, M.; Waks, S. Engineering Systems Thinking: A Multifunctional Definition. *Syst. Pract. Action Res.* **2001**, *14* (3), 361–379. <https://doi.org/10.1023/A:1011363516269>.
- (200) Dori, D. *Model-Based Systems Engineering with OPM and SysML*; Springer New York: New York, NY, 2016. <https://doi.org/10.1007/978-1-4939-3295-5>.
- (201) 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>.
- (202) Lavi, R.; Dori, Y. J.; Dori, D. Assessing Novelty and Systems Thinking in Conceptual Models of Technological Systems. *IEEE Trans. Educ.* **2021**, *64* (2), 155–162. <https://doi.org/10.1109/TE.2020.3022238>.
- (203) Lavi, R.; Dori, Y. J.; Wengrowicz, N.; Dori, D. Model-Based Systems Thinking: Assessing Engineering Student Teams. *IEEE Trans. Educ.* **2020**, *63* (1), 39–47. <https://doi.org/10.1109/TE.2019.2948807>.
- (204) Plate, R. Assessing Individuals’ Understanding of Nonlinear Causal Structures in Complex Systems. *Syst. Dyn. Rev.* **2010**, *26* (1), 19–33. <https://doi.org/10.1002/sdr.432>.

- (205) Ben-zvi-Assarf, O.; Orion, N. A Study of Junior High Students' Perceptions of the Water Cycle. *J. Geosci. Educ.* **2005**, *53* (4), 366–373. <https://doi.org/10.5408/1089-9995-53.4.366>.
- (206) Tripto, J.; Assaraf, O. B. Z.; Snapir, Z.; Amit, M. How Is the Body's Systemic Nature Manifested amongst High School Biology Students? *Instr. Sci.* **2017**, *45* (1), 73–98. <https://doi.org/10.1007/s11251-016-9390-0>.
- (207) Reiner, M.; Eilam, B. Conceptual Classroom Environment - a System View of Learning. *Int. J. Sci. Educ.* **2001**, *23* (6), 551–568. <https://doi.org/10.1080/095006901300172458>.
- (208) Raia, F. Students' Understanding of Complex Dynamic Systems. *J. Geosci. Educ.* **2005**, *53* (3), 297–308. <https://doi.org/10.5408/1089-9995-53.3.297>.
- (209) Jacobson, M. J.; Wilensky, U. Complex Systems in Education: Scientific and Educational Importance and Implications for the Learning Sciences. *J. Learn. Sci.* **2006**, *15* (1), 11–34. https://doi.org/10.1207/s15327809jls1501_4.
- (210) Remington-Doucette, S. M.; Hiller Connell, K. Y.; Armstrong, C. M.; Musgrove, S. L. Assessing Sustainability Education in a Transdisciplinary Undergraduate Course Focused on Real-world Problem Solving: A Case for Disciplinary Grounding. *Int. J. Sustain. High. Educ.* **2013**, *14* (4), 404–433. <https://doi.org/10.1108/IJSHE-01-2012-0001>.
- (211) Bodner, G. M.; Herron, J. D. Problem-Solving in Chemistry. In *Chemical Education: Towards Research-based Practice*; Gilbert, J. K., Jong, O., Justi, R., Treagust, D. F., Driel, J. H., Eds.; Science & Technology Education Library; Kluwer Academic Publishers: Dordrecht, 2003; Vol. 17, pp 235–266. https://doi.org/10.1007/0-306-47977-X_11.
- (212) Hogan, K. Assessing Students' Systems Reasoning in Ecology. *J. Biol. Educ.* **2000**, *35* (1), 22–28. <https://doi.org/10.1080/00219266.2000.9655731>.
- (213) Hokayem, H.; Ma, J.; Jin, H. A Learning Progression for Feedback Loop Reasoning at Lower Elementary Level. *J. Biol. Educ.* **2015**, *49* (3), 246–260. <https://doi.org/10.1080/00219266.2014.943789>.
- (214) Pintó, R.; Couso, D. *Contributions from Science Education Research*; Kluwer: Dordrecht, 2007. <https://doi.org/10.1007/978-1-4020-5032-9>
- (215) Demssie, Y. N.; Biemans, H. J. A.; Wesselink, R.; Mulder, M. Fostering Students' Systems Thinking Competence for Sustainability by Using Multiple Real-World Learning Approaches. *Environ. Educ. Res.* **2023**, *29* (2), 261–286. <https://doi.org/10.1080/13504622.2022.2141692>.

- (216) Gilbert, L. A.; Gross, D. S.; Kreutz, K. J. Developing Undergraduate Students' Systems Thinking Skills with an InTeGrate Module. *J. Geosci. Educ.* **2019**, *67* (1), 34–49. <https://doi.org/10.1080/10899995.2018.1529469>.
- (217) Johnson-Laird, P. N. Mental Models and Deduction. *Trends in Cognitive Sciences.* **2001**, *5* (10), 434–442. [https://doi.org/10.1016/S1364-6613\(00\)01751-4](https://doi.org/10.1016/S1364-6613(00)01751-4).
- (218) Duit, R.; Treagust, D. F. Conceptual Change: A Powerful Framework for Improving Science Teaching and Learning. *Int. J. Sci. Educ.* **2003**, *25* (6), 671–688. <https://doi.org/10.1080/09500690305016>.
- (219) Novak, J. D.; Cañas, A. J. Theoretical Origins of Concept Maps, How to Construct Them, and Uses in Education. *Reflecting Educ.* **2007**, *3* (1), 29–42. <http://cmap.ihmc.us/Publications/ResearchPapers/TheoryUnderlyingConceptMaps.pdf>.
- (220) Novak, J. D. Concept Maps and Vee Diagrams: Two Metacognitive Tools to Facilitate Meaningful Learning. *Instr. Sci.* **1990**, *19* (1), 29–52. <https://doi.org/10.1007/BF00377984>.
- (221) Tripto, J.; Assaraf, O. B. Z.; Amit, M. Recurring Patterns in the Development of High School Biology Students' System Thinking over Time. *Instr. Sci.* **2018**, *46* (5), 639–680. <https://doi.org/10.1007/s11251-018-9447-3>.
- (222) Novak, J. D.; Gowin, D. B. *Learning How to Learn*; Cambridge University Press: Cambridge, New York, 1984.
- (223) Ruiz-Primo, M. A.; Shavelson, R. J. Problems and Issues in the Use of Concept Maps in Science Assessment. *J. Res. Sci. Teach.* **1996**, *33* (6), 569–600. [https://doi.org/10.1002/\(SICI\)1098-2736\(199608\)33:6<569::AID-TEA1>3.0.CO;2-M](https://doi.org/10.1002/(SICI)1098-2736(199608)33:6<569::AID-TEA1>3.0.CO;2-M).
- (224) Herbert, B. E. Student Understanding of Complex Earth Systems. In *Earth and Mind: How Geologists Think and Learn about the Earth*; Geological Society of America, 2006. [https://doi.org/10.1130/2006.2413\(07\)](https://doi.org/10.1130/2006.2413(07)).
- (225) Sell, K. S.; Herbert, B. E.; Stuessy, C. L.; Schielack, J. Supporting Student Conceptual Model Development of Complex Earth Systems Through the Use of Multiple Representations and Inquiry. *J. Geosci. Educ.* **2006**, *54* (3), 396–407. <https://doi.org/10.5408/1089-9995-54.3.396>.
- (226) Libarkin, J. C.; Anderson, S. W.; Science, J. D.; Beilfuss, M.; Boone, W. Qualitative Analysis of College Students' Ideas about the Earth: Interviews and Open-Ended Questionnaires. *J. Geosci. Educ.* **2005**, *53* (1), 17–26. <https://doi.org/10.5408/1089-9995-53.1.17>.
- (227) Gero, A.; Zach, E. High School Programme in Electro-Optics: A Case Study on Interdisciplinary Learning and Systems Thinking. *Int. J. Eng. Ed.* **2014**, *30* (5), 1190–1199.

- <https://www.scopus.com/record/display.uri?eid=2-s2.0-84908512774&origin=inward&txGid=6d3762f40de92244add14dc14fff0193>
- (228) Dos Santos, A. C. K.; Ogborn, J. Sixth Form Students' Ability to Engage in Computational Modelling. *J. Comput. Assist. Learn.* **1994**, *10* (3), 182–200. <https://doi.org/10.1111/j.1365-2729.1994.tb00294.x>.
 - (229) Rosenkränzer, F.; Hörsch, C.; Schuler, S.; Riess, W. Student Teachers' Pedagogical Content Knowledge for Teaching Systems Thinking: Effects of Different Interventions. *Int. J. Sci. Educ.* **2017**, *39* (14), 1932–1951. <https://doi.org/10.1080/09500693.2017.1362603>.
 - (230) Rosenkränzer, F.; Kramer, T.; Hörsch, C.; Schuler, S.; Rieß, W. Promoting Student Teachers' Content Related Knowledge in Teaching Systems Thinking: Measuring Effects of an Intervention through Evaluating a Videotaped Lesson. *High. Educ. Stud.* **2016**, *6* (4), 156. <https://doi.org/10.5539/hes.v6n4p156>.
 - (231) Roychoudhury, A.; Shepardson, D. P.; Hirsch, A.; Niyogi, D.; Mehta, J.; Top, S. The Need to Introduce System Thinking in Teaching Climate Change. *Science Educator.* **2017**, *25* (2), 73–81. <https://eric.ed.gov/?id=EJ1132081>
 - (232) Schuler, S.; Fanta, D.; Rosenkraenzer, F.; Riess, W. Systems Thinking within the Scope of Education for Sustainable Development (ESD) – a Heuristic Competence Model as a Basis for (Science) Teacher Education. *J. Geogr. High. Educ.* **2018**, *42* (2), 192–204. <https://doi.org/10.1080/03098265.2017.1339264>.
 - (233) Skaza, H. J. Assessing the Effect of Simulation Models on Systems Learning in an Introductory Environmental Science Course. *UNLV Theses, Dissertations, Professional Papers, and Capstones* **2010**. <https://doi.org/10.34870/1343360>.
 - (234) Whalen, J. M.; Matlin, S. A.; Holme, T. A.; Stewart, J. J.; Mahaffy, P. G. A Systems Approach to Chemistry Is Required to Achieve Sustainable Transformation of Matter: The Case of Ammonia and Reactive Nitrogen. *ACS Sustainable Chemistry & Engineering.* **2022**, *10* (39), 12933–12947. DOI: 10.1021/acssuschemeng.2c03159.
 - (235) *Project Details: Learning Objectives and Strategies for Infusing Systems Thinking into (Post)-Secondary General Chemistry Education*. International Union of Pure and Applied Chemistry. https://iupac.org/projects/project-details/?project_nr=2017-010-1-050 (accessed 2020-08-25).
 - (236) Aubrecht, K. B.; Bourgeois, M.; Brush, E. J.; MacKellar, J.; Wissinger, J. E. Integrating Green Chemistry in the Curriculum: Building Student Skills in Systems Thinking, Safety, and Sustainability. *J. Chem. Educ.* **2019**, *96* (12), 2872–2880. <https://doi.org/10.1021/acs.jchemed.9b00354>.

- (237) Whitesides, G. M. Reinventing Chemistry. *Angew. Chem. Int. Ed.* **2015**, *54* (11), 3196–3209. <https://doi.org/10.1002/anie.201410884>.
- (238) Constable, D. J. C. The Practice of Chemistry Still Needs to Change. *Curr. Opin. Green Sustain. Chem.* **2017**, *7*, 60–62. <https://doi.org/10.1016/j.cogsc.2017.08.002>.
- (239) ACS. *Committee on Professional Training*. <https://www.acs.org/about/governance/committees/professional-training.html> (accessed 2024-03-14).
- (240) Ho, F. M. Turning Challenges into Opportunities for Promoting Systems Thinking through Chemistry Education. *J. Chem. Educ.* **2019**, *96* (12), 2764–2776. <https://doi.org/10.1021/acs.jchemed.9b00309>.
- (241) Perosa, A.; Gonella, F.; Spagnolo, S. Systems Thinking: Adopting an Emergy Perspective as a Tool for Teaching Green Chemistry. *J. Chem. Educ.* **2019**, *96* (12), 2784–2793. <https://doi.org/10.1021/acs.jchemed.9b00377>.
- (242) Hurst, G. A.; Slootweg, J. C.; Balu, A. M.; Climent-Bellido, M. S.; Gomera, A.; Gomez, P.; Luque, R.; Mammìno, 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>.
- (243) Fowler, W. C.; Ting, J. M.; Meng, S.; Li, L.; Tirrell, M. V. Integrating Systems Thinking into Teaching Emerging Technologies. *J. Chem. Educ.* **2019**, *96* (12), 2805–2813. <https://doi.org/10.1021/acs.jchemed.9b00280>.
- (244) Chiu, M.-H.; Mamlok-Naman, R.; Apotheker, J. Identifying Systems Thinking Components in the School Science Curricular Standards of Four Countries. *J. Chem. Educ.* **2019**, *96* (12), 2814–2824. <https://doi.org/10.1021/acs.jchemed.9b00298>.
- (245) Michalopoulou, E.; Shallcross, D. E.; Atkins, E.; Tierney, A.; Norman, N. C.; Preist, C.; O'Doherty, S.; Saunders, R.; Birkett, A.; Willmore, C.; Ninos, I. The End of Simple Problems: Repositioning Chemistry in Higher Education and Society Using a Systems Thinking Approach and the United Nations' Sustainable Development Goals as a Framework. *J. Chem. Educ.* **2019**, *96* (12), 2825–2835. <https://doi.org/10.1021/acs.jchemed.9b00270>.
- (246) Dicks, A. P.; D'eon, J. C.; Morra, B.; Kutas Chisu, C.; Quinlan, K. B.; Cannon, A. S. A Systems Thinking Department: Fostering a Culture of Green Chemistry Practice among Students. *J. Chem. Educ.* **2019**, *96* (12), 2836–2844. <https://doi.org/10.1021/acs.jchemed.9b00287>.

- (247) Blatti, J. L.; Garcia, J.; Cave, D.; Monge, F.; Cuccinello, A.; Portillo, J.; Juarez, B.; Chan, E.; Schwebel, F. Systems Thinking in Science Education and Outreach toward a Sustainable Future. *J. Chem. Educ.* **2019**, *96* (12), 2852–2862. <https://doi.org/10.1021/acs.jchemed.9b00318>.
- (248) Ginzburg, A. L.; Check, C. E.; Hovekamp, D. P.; Sillin, A. N.; Brett, J.; Eshelman, H.; Hutchison, J. E. Experiential Learning To Promote Systems Thinking in Chemistry: Evaluating and Designing Sustainable Products in a Polymer Immersion Lab. *J. Chem. Educ.* **2019**, *96* (12), 2863–2871. <https://doi.org/10.1021/acs.jchemed.9b00336>.
- (249) Mammino, L. Roles of Systems Thinking within Green Chemistry Education: Reflections from Identified Challenges in a Disadvantaged Context. *J. Chem. Educ.* **2019**, *96* (12), 2881–2887. <https://doi.org/10.1021/acs.jchemed.9b00302>.
- (250) Aubrecht, K. B.; Dori, Y. J.; Holme, T. A.; Lavi, R.; Matlin, S. A.; Orgill, M.; Skaza-Acosta, H. Graphical Tools for Conceptualizing Systems Thinking in Chemistry Education. *J. Chem. Educ.* **2019**, *96* (12), 2888–2900. <https://doi.org/10.1021/acs.jchemed.9b00314>.
- (251) Kornfeld, J.; Stokoe, S. Introducing Chemistry through the Lens of Earth's Systems: What Role Can Systems Thinking Play in Developing Chemically and Environmentally Literate Citizens? *J. Chem. Educ.* **2019**, *96* (12), 2910–2917. <https://doi.org/10.1021/acs.jchemed.9b00263>.
- (252) Kim, S.; Choi, H.; Paik, S.-H. Using a Systems Thinking Approach and a Scratch Computer Program To Improve Students' Understanding of the Brønsted–Lowry Acid–Base Model. *J. Chem. Educ.* **2019**, *96* (12), 2926–2936. <https://doi.org/10.1021/acs.jchemed.9b00210>.
- (253) Chapman, S.; Herniman, J. M.; Langley, G. J.; Raja, R.; Logothetis, T. A. Redox Aluminophosphates: Applying Fundamental Undergraduate Theory To Solve Global Challenges in the Chemical Industry. *J. Chem. Educ.* **2019**, *96* (12), 2937–2946. <https://doi.org/10.1021/acs.jchemed.9b00288>.
- (254) Cooper, P. D.; Walser, J. Total Chemical Footprint of an Experiment: A Systems Thinking Approach to Teaching Rovibrational Spectroscopy. *J. Chem. Educ.* **2019**, *96* (12), 2947–2951. <https://doi.org/10.1021/acs.jchemed.9b00405>.
- (255) Zowada, C.; Siol, A.; Gulacar, O.; Eilks, I. Phosphate Recovery as a Topic for Practical and Interdisciplinary Chemistry Learning. *J. Chem. Educ.* **2019**, *96* (12), 2952–2958. <https://doi.org/10.1021/acs.jchemed.8b01000>.
- (256) 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>.
- (257) Eaton, A. C.; Delaney, S.; Schultz, M. Situating Sustainable Development within Secondary Chemistry Education via Systems Thinking: A Depth Study Approach. *J. Chem. Educ.* **2019**, *96* (12), 2968–2974. <https://doi.org/10.1021/acs.jchemed.9b00266>.
- (258) Zuin, V. G.; Segatto, M. L.; Zandonai, D. P.; Grosseli, G. M.; Stahl, A.; Zanotti, K.; Andrade, R. S. Integrating Green and Sustainable Chemistry into Undergraduate Teaching Laboratories: Closing and Assessing the Loop on the Basis of a Citrus Biorefinery Approach for the Biocircular Economy in Brazil. *J. Chem. Educ.* **2019**, *96* (12), 2975–2983. <https://doi.org/10.1021/acs.jchemed.9b00286>.
- (259) Schwarzman, M. R.; Buckley, H. L. Not Just an Academic Exercise: Systems Thinking Applied to Designing Safer Alternatives. *J. Chem. Educ.* **2019**, *96* (12), 2984–2992. <https://doi.org/10.1021/acs.jchemed.9b00345>.
- (260) Murphy, K. C.; Dilip, M.; Quattrucci, J. G.; Mitroka, S. M.; Andreatta, J. R. Sustainable Consumer Choices: An Outreach Program Exploring the Environmental Impact of Our Consumer Choices Using a Systems Thinking Model and Laboratory Activities. *J. Chem. Educ.* **2019**, *96* (12), 2993–2999. <https://doi.org/10.1021/acs.jchemed.9b00400>.
- (261) Donahue, C. J. Reimagining the Materials Tetrahedron. *J. Chem. Educ.* **2019**, *96* (12), 2682–2688. <https://doi.org/10.1021/acs.jchemed.9b00016>.
- (262) Constable, D. J. C.; Jiménez-González, C.; Matlin, S. A. Navigating Complexity Using Systems Thinking in Chemistry, with Implications for Chemistry Education. *J. Chem. Educ.* **2019**, *96* (12), 2689–2699. <https://doi.org/10.1021/acs.jchemed.9b00368>.
- (263) Blonder, R.; Rosenfeld, S. Integrating the Human Element in the Responsible Research and Innovation Framework into Systems Thinking Approaches for Teachers' Professional Development. *J. Chem. Educ.* **2019**, *96* (12), 2700–2703. <https://doi.org/10.1021/acs.jchemed.9b00387>.
- (264) Gentili, P. L. Designing and Teaching a Novel Interdisciplinary Course on Complex Systems To Prepare New Generations To Address 21st-Century Challenges. *J. Chem. Educ.* **2019**, *96* (12), 2704–2709. <https://doi.org/10.1021/acs.jchemed.9b00027>.
- (265) Lasker, G. A. Connecting Systems Thinking and Service Learning in the Chemistry Classroom. *J. Chem. Educ.* **2019**, *96* (12), 2710–2714. <https://doi.org/10.1021/acs.jchemed.9b00344>.
- (266) Fisher, M. A. Systems Thinking and Educating the Heads, Hands, and Hearts of Chemistry Majors. *J. Chem. Educ.* **2019**, *96* (12), 2715–2719. <https://doi.org/10.1021/acs.jchemed.9b00346>.

- (267) Mackenzie, L. S.; Tyrrell, H.; Thomas, R.; Matharu, A. S.; Clark, J. H.; Hurst, G. A. Valorization of Waste Orange Peel to Produce Shear-Thinning Gels. *J. Chem. Educ.* **2019**, *96* (12), 3025–3029. <https://doi.org/10.1021/acs.jchemed.8b01009>.
- (268) Pfab, E.; Filiciotto, L.; Luque, R. The Dark Side of Biomass Valorization: A Laboratory Experiment To Understand Humin Formation, Catalysis, and Green Chemistry. *J. Chem. Educ.* **2019**, *96* (12), 3030–3037. <https://doi.org/10.1021/acs.jchemed.9b00410>.
- (269) Sharma, R. K.; Yadav, S.; Gupta, R.; Arora, G. Synthesis of Magnetic Nanoparticles Using Potato Extract for Dye Degradation: A Green Chemistry Experiment. *J. Chem. Educ.* **2019**, *96* (12), 3038–3044. <https://doi.org/10.1021/acs.jchemed.9b00384>.
- (270) Diekemper, D.; Schnick, W.; Schwarzer, S. Microwave Synthesis of a Prominent LED Phosphor for School Students: Chemistry's Contribution to Sustainable Lighting. *J. Chem. Educ.* **2019**, *96* (12), 3018–3024. <https://doi.org/10.1021/acs.jchemed.9b00464>.
- (271) Maharaj, F. D. R.; Wu, W.; Zhou, Y.; Schwanz, L. T.; Marshak, M. P. Exploring Real-World Applications of Electrochemistry by Constructing a Rechargeable Lithium-Ion Battery. *J. Chem. Educ.* **2019**, *96* (12), 3014–3017. <https://doi.org/10.1021/acs.jchemed.9b00328>.
- (272) Miller, J. L.; Wentzel, M. T.; Clark, J. H.; Hurst, G. A. Green Machine: A Card Game Introducing Students to Systems Thinking in Green Chemistry by Strategizing the Creation of a Recycling Plant. *J. Chem. Educ.* **2019**, *96* (12), 3006–3013. <https://doi.org/10.1021/acs.jchemed.9b00278>.
- (273) Committee on Communicating Chemistry in Informal Settings; Board on Chemical Sciences and Technology; Division on Earth and Life Studies; Board on Science Education; Division of Behavioral and Social Sciences and Education; National Academies of Sciences, Engineering, and Medicine. *Effective Chemistry Communication in Informal Environments*; National Academies Press: Washington, D.C., 2016; p 21790. <https://doi.org/10.17226/21790>.
- (274) Mahaffy, P. G.; Elgersma, A. K. Systems Thinking, the Molecular Basis of Sustainability and the Planetary Boundaries Framework: Complementary Core Competencies for Chemistry Education. *Curr. Opin. Green Sustain. Chem.* **2022**, *37*, 100663. <https://doi.org/10.1016/j.cogsc.2022.100663>.
- (275) *Planetary Boundaries*. Stockholm Resilience Centre. <https://www.stockholmresilience.org/research/planetary-boundaries.html> (accessed 2024-06-13).
- (276) Schwendimann, Beat. A. Concept Maps as Versatile Tools to Integrate Complex Ideas: From Kindergarten to Higher and Professional Education. *Knowl. Manag. E-Learn. Int. J.* **2015**, *73*–99. <https://doi.org/10.34105/j.kmel.2015.07.006>.

- (277) Regis, A.; Albertazzi, P. G.; Roletto, E. Concept Maps in Chemistry Education. *J. Chem. Educ.* **1996**, *73* (11), 1084. <https://doi.org/10.1021/ed073p1084>.
- (278) 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>.
- (279) 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>.
- (280) Villafañe, S. M.; Xu, X.; Raker, J. R. Self-Efficacy and Academic Performance in First-Semester Organic Chemistry: Testing a Model of Reciprocal Causation. *Chem. Educ. Res. Pract.* **2016**, *17* (4), 973–984. <https://doi.org/10.1039/c6rp00119j>.
- (281) Liu, Y.; Ferrell, B.; Barbera, J.; Lewis, J. E. Development and Evaluation of a Chemistry-Specific Version of the Academic Motivation Scale (AMS-Chemistry). *Chem. Educ. Res. Pract.* **2017**, *18* (1), 191–213. <https://doi.org/10.1039/c6rp00200e>.
- (282) Else-Quest, N. M.; Mineo, C. C.; Higgins, A. Math and Science Attitudes and Achievement at the Intersection of Gender and Ethnicity. *Psychol. Women Q.* **2013**, *37* (3), 293–309. <https://doi.org/10.1177/0361684313480694>.
- (283) Leslie, S.-J.; Cimpian, A.; Meyer, M.; Freeland, E. Expectations of Brilliance Underlie Gender Distributions across Academic Disciplines. *Science* **2015**, *347* (6219), 262–265. <https://doi.org/10.1126/science.1261375>.
- (284) Catsambis, S. Gender, Race, Ethnicity, and Science Education in the Middle Grades. *J. Res. Sci. Teach.* **1995**, *32* (3), 243–257. <https://doi.org/10.1002/tea.3660320305>.
- (285) SSHRC. *Imagining Canada's Future: Asking tomorrow's questions today*. https://www.sshrc-crsh.gc.ca/society-societe/community-communite/Imagining_Canadas_Future-Imaginer_l_avenir_du_Canada-eng.aspx (accessed 2019-11-11).
- (286) Urry, M. Science and Gender: Scientists Must Work Harder on Equality. *Nature* **2015**, *528* (7583), 471–473. <https://doi.org/10.1038/528471a>.
- (287) Wall, K. *Persistence and Representation of Women in STEM Programs*. 2019. <https://eric.ed.gov/?id=ED594933> (accessed 2024-07-11).
- (288) Malcom, S.; Feder, M. *Barriers and Opportunities for 2-Year and 4-Year STEM Degrees: Systemic Change to Support Students' Diverse Pathways*; 2016. <https://doi.org/10.17226/21739>.

- (289) Raycroft, M. A. R.; Flynn, A. B. What Works? What's Missing? An Evaluation Model for Science Curricula That Analyses Learning Outcomes through Five Lenses. *Chem. Educ. Res. Pract.* **2020**. <https://doi.org/10.1039/C9RP00157C>.
- (290) Chiu, M.-H.; Mamlok-Naman, R.; Apotheker, J. Identifying Systems Thinking Components in the School Science Curricular Standards of Four Countries. *J. Chem. Educ.* **2019**, *96* (12), 2814–2824. <https://doi.org/10.1021/acs.jchemed.9b00298>.
- (291) Elmgren, M.; Ho, F.; Åkesson, E.; Schmid, S.; Towns, M. Comparison and Evaluation of Learning Outcomes from an International Perspective: Development of a Best-Practice Process. *J. Chem. Educ.* **2015**, *92* (3), 427–432. <https://doi.org/10.1021/ed500542b>.
- (292) 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>.
- (293) Delaney, S.; Ferguson, J. P.; Schultz, M. Exploring Opportunities to Incorporate Systems Thinking into Secondary and Tertiary Chemistry Education through Practitioner Perspectives. *Int. J. Sci. Educ.* **2021**, *43* (16), 2618–2639. <https://doi.org/10.1080/09500693.2021.1980631>.
- (294) 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>.
- (295) York, S.; Orgill, M. Experienced Tertiary Instructors' Perceptions of the Benefits and Challenges of Systems Thinking in Chemistry Education. *J. Chem. Educ.* **2024**, *101* (1), 10–23. <https://doi.org/10.1021/acs.jchemed.3c01000>.
- (296) Talanquer, V. Some Insights into Assessing Chemical Systems Thinking. *J. Chem. Educ.* **2019**, *96* (12), 2918–2925. <https://doi.org/10.1021/acs.jchemed.9b00218>.
- (297) An, J.; Loppnow, G. R.; Holme, T. A. Measuring the Impact of Incorporating Systems Thinking into General Chemistry on Affective Components of Student Learning. *Can. J. Chem.* **2021**, *99* (8), 698–705. <https://doi.org/10.1139/cjc-2020-0218>.
- (298) Liang, Y.; Xiao, Z.; Wang, S.; Li, Y.; Li, H. An Interdisciplinary Practical Project for Preservice Science Teachers: Visualizing Climate Change Based on Systems Thinking. *J. Chem. Educ.* **2024**, *101* (7), 2682–2692. <https://doi.org/10.1021/acs.jchemed.3c01271>.
- (299) Holme, T. Using the Chemistry of Pharmaceuticals to Introduce Sustainable Chemistry and Systems Thinking in General Chemistry. *Sustain. Chem. Pharm.* **2020**, *16*, 100234. <https://doi.org/10.1016/j.scp.2020.100234>.

- (300) Armstrong, D.; Poë, J. C. The Science of Human Health—A Context-Based Chemistry Course for Non-Science Majors Incorporating Systems Thinking. *J. Chem. Educ.* **2020**, *97* (11), 3957–3965. <https://doi.org/10.1021/acs.jchemed.0c00887>.
- (301) Hurst, G. A. Systems Thinking Approaches for International Green Chemistry Education. *Curr. Opin. Green Sustain. Chem.* **2020**, *21*, 93–97. <https://doi.org/10.1016/j.cogsc.2020.02.004>.
- (302) Lees, M.; Wentzel, M. T.; Clark, J. H.; Hurst, G. A. Green Tycoon: A Mobile Application Game to Introduce Biorefining Principles in Green Chemistry. *J. Chem. Educ.* **2020**, *97* (7), 2014–2019. <https://doi.org/10.1021/acs.jchemed.0c00363>.
- (303) Reyes, K. M. D.; Bruce, K.; Shetranjiwalla, S. Green Chemistry, Life Cycle Assessment, and Systems Thinking: An Integrated Comparative-Complementary Chemical Decision-Making Approach. *J. Chem. Educ.* **2023**, *100* (1), 209–220. <https://doi.org/10.1021/acs.jchemed.2c00647>.
- (304) Delaney, S.; Donnelly, S.; Rochette, E.; Orgill, M. A System Mapping Activity to Visualize Lithium's Interconnectedness to Societal and Environmental Aspects of the Green Energy Transition. *Chem. Teach. Int.* **2024**, *0* (0). <https://doi.org/10.1515/cti-2023-0051>.
- (305) MacDonald, R. P.; Pattison, A. N.; Cornell, S. E.; Elgersma, A. K.; Greidanus, S. N.; Visser, S. N.; Hoffman, M.; Mahaffy, P. G. An Interactive Planetary Boundaries Systems Thinking Learning Tool to Integrate Sustainability into the Chemistry Curriculum. *J. Chem. Educ.* **2022**, *99* (10), 3530–3539. <https://doi.org/10.1021/acs.jchemed.2c00659>.
- (306) King's Centre for Visualization in Science, J. *Planetary Boundaries*. <https://applets.kcvs.ca/PlanetaryBoundaries/> (accessed 2024-06-14).
- (307) King's Centre for Visualization in Science. *SOCKit*. <https://applets.kcvs.ca/socket/> (accessed 2024-06-14).
- (308) International Union of Pure and Applied Chemistry (IUPAC). *Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+)*. <https://iupac.org/project/2020-014-3-050/> (accessed 2024-03-15).
- (309) *Sustainability and Systems Thinking In Chemistry Education*. <https://sastice.com/> (accessed 2024-01-25).
- (310) Talanquer, V.; Szozda, A. R. An Educational Framework for Teaching Chemistry Using a Systems Thinking Approach. *J. Chem. Educ.* **2024**, *101* (5), 1785–1792. <https://doi.org/10.1021/acs.jchemed.4c00216>.
- (311) *Teaching Chemistry Concepts and Ideas using Systems Thinking*. Systems Thinking in Chemistry Education. <https://sites.google.com/view/sastice/home> (accessed 2024-06-13).

- (312) Tümay, H. Systems Thinking in Chemistry and Chemical Education: A Framework for Meaningful Conceptual Learning and Competence in Chemistry. *J. Chem. Educ.* **2023**, *100* (10), 3925–3933. <https://doi.org/10.1021/acs.jchemed.3c00474>.
- (313) Talanquer, V.; Bucat, R.; Tasker, R.; Mahaffy, P. G. Lessons from a Pandemic: Educating for Complexity, Change, Uncertainty, Vulnerability, and Resilience. *J. Chem. Educ.* **2020**, *97* (9), 2696–2700. <https://doi.org/10.1021/acs.jchemed.0c00627>.
- (314) Gess-Newsome, J.; Southerland, S. A.; Johnston, A.; Woodbury, S. Educational Reform, Personal Practical Theories, and Dissatisfaction: The Anatomy of Change in College Science Teaching. *Am. Educ. Res. J.* **2003**, *40* (3), 731–767. <https://doi.org/10.3102/00028312040003731>.
- (315) Clarke, D.; Hollingsworth, H. Elaborating a Model of Teacher Professional Growth. *Teaching and Teacher Education*, *18*(8), 947–967. *Teach. Teach. Educ.* **2002**, *18*, 947–967. [https://doi.org/10.1016/S0742-051X\(02\)00053-7](https://doi.org/10.1016/S0742-051X(02)00053-7).
- (316) Shadle, S. E.; Marker, A.; Earl, B. Faculty Drivers and Barriers: Laying the Groundwork for Undergraduate STEM Education Reform in Academic Departments. *Int. J. STEM Educ.* **2017**, *4* (1), 8. <https://doi.org/10.1186/s40594-017-0062-7>.
- (317) Henderson, C.; Beach, A.; Finkelstein, N. Facilitating Change in Undergraduate STEM Instructional Practices: An Analytic Review of the Literature. *J. Res. Sci. Teach.* **2011**, *48* (8), 952–984. <https://doi.org/10.1002/tea.20439>.
- (318) Woodbury, S.; Gess-Newsome, J. Overcoming the Paradox of Change without Difference: A Model of Change in the Arena of Fundamental School Reform. *Educ. Policy* **2002**, *16* (5), 763–782. <https://doi.org/10.1177/089590402237312>.
- (319) Şen, Ö. F.; Sari, U. From Traditional to Reform-Based Teaching Beliefs and Classroom Practices of Elementary Science Teachers. *Int. J. Innov. Sci. Math. Educ.* **2018**, *26* (6), 76–95. <https://openjournals.library.sydney.edu.au/CAL/article/view/12792>
- (320) Southerland, S. A.; Granger, E. M.; Hughes, R.; Enderle, P.; Ke, F.; Roseler, K.; Saka, Y.; Tekkumrukisa, M. Essential Aspects of Science Teacher Professional Development. *AERA Open* **2016**, *2* (4), 233285841667420. <https://doi.org/10.1177/2332858416674200>.
- (321) Wong, S.; Luft, J. Secondary Science Teachers' Beliefs and Persistence: A Longitudinal Mixed-Methods Study. *J. Sci. Teach. Educ.* **2015**, *26*, 619–645. <https://doi.org/10.1007/s10972-015-9441-4>.

- (322) Dolphin, G.; Tillotson, J. "Uncentering" Teacher Beliefs: The Expressed Epistemologies of Secondary Science Teachers and How They Relate to Teacher Practice. *Int. J. Environ. Sci. Educ.* **2015**, 2015, 21–38. <https://doi.org/10.12973/ijese.2015.228a>.
- (323) Enderle, P.; Dentzau, M.; Roseler, K.; Southerland, S.; Granger, E.; Hughes, R.; Golden, B.; Saka, Y. Examining the Influence of RETs on Science Teacher Beliefs and Practice. *Sci. Educ.* **2014**, 98 (6), 1077–1108. <https://doi.org/10.1002/sce.21127>.
- (324) Austin, A. E. *Promoting Evidence-Based Change in Undergraduate Science Education*; Paper Commissioned by the National Academies National Research Council Board on Science Education; The National Academies: Washington, D.C., 2011.
- (325) *Transforming Institutions: Undergraduate STEM Education for the 21st Century*; Weaver, G. C., Ed.; Purdue University Press: West Lafayette, Indiana, 2016.
- (326) Lemke, J. L.; Sabelli, N. H. Complex Systems and Educational Change: Towards a New Research Agenda. *Educ. Philos. Theory* **2008**, 40 (1), 118–129. <https://doi.org/10.1111/j.1469-5812.2007.00401.x>.
- (327) Scileppi, J. A. *A Systems View of Education: A Model for Change*; University Press of America: Lanham, MD, 1984.
- (328) Celestino, T.; Marchetti, F. Surveying Italian and International Baccalaureate Teachers to Compare Their Opinions on System Concept and Interdisciplinary Approaches in Chemistry Education. *J. Chem. Educ.* **2020**, 97 (10), 3575–3587. <https://doi.org/10.1021/acs.jchemed.9b00293>.
- (329) Schunk, D. H. *Learning Theories: An Educational Perspective*, 6th ed.; Pearson: Boston, 2012.
- (330) Schunk, D. H. *Learning Theories: An Educational Perspective (6th Edition)*; Pearson Education Inc: Boston, MA, 2012; Vol. 5.
- (331) Mayer, R. E. Information Processing. In *APA educational psychology handbook, Vol 1: Theories, constructs, and critical issues.*; Harris, K. R., Graham, S., Urdan, T., McCormick, C. B., Sinatra, G. M., Sweller, J., Eds.; American Psychological Association: Washington, 2012; pp 85–99. <https://doi.org/10.1037/13273-004>.
- (332) 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>.
- (333) Ausubel, D. P.; Novak, J. D.; Hanesian, H. *Educational Psychology: A Cognitive View*, 2nd ed.; New York (N.Y.): Holt, 1968.

- (334) Galloway, K. R.; Bretz, S. L. Using Cluster Analysis to Characterize Meaningful Learning in a First-Year University Chemistry Laboratory Course. *Chem Educ Res Pr.* **2015**, *16* (4), 879–892. <https://doi.org/10.1039/C5RP00077G>.
- (335) Cobb, P. Where Is the Mind? Constructivist and Sociocultural Perspectives on Mathematical Development. *Educ. Res.* **1994**, *23* (7), 13–20. <https://doi.org/10.3102/0013189X023007013>.
- (336) 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>.
- (337) Carle, M. S.; Flynn, A. B. Essential Learning Outcomes for Delocalization (Resonance) Concepts: How Are They Taught, Practiced, and Assessed in Organic Chemistry? *Chem. Educ. Res. Pract.* **2020**, *21* (2), 622–637. <https://doi.org/10.1039/C9RP00203K>.

Chapter 2: Investigating educators' perspectives toward systems thinking in chemistry education from international contexts

2.1 Introduction to the manuscript in Chapter 2

Educational change for new teaching and learning approaches can be slow.^{1,2} Educators' beliefs about teaching and learning, and personal and contextual factors influence educators' implementation of evidence-based instructional practices but there is a paucity of research on this topic.^{1,2} Several chemistry education researchers starting investigating educators' perspectives on ST including ourselves.³⁻⁵ If a ST approach is to be successfully integrated in chemistry education, their perspectives and contexts must be deeply understood so their needs can be addressed. We dive into the research on educators' perspectives in this chapter.

Chapter 2 describes our work on using an educational change model to investigate the interconnected factors that enable or hinder chemistry educators' willingness or adoption of ST in chemistry education. We analyzed 56 secondary and postsecondary chemistry educators' responses from an educator questionnaire and identified four key themes. We connected our findings to the educational change model by indicating specific aspects that experts and administrators need to address to reduce barriers for STICE implementation and engagement.

This was the first study I conducted during my doctoral studies; therefore, it was not a surprise that I encountered challenges such as conducting several attempts for the educator questionnaire. Despite my Bachelor of Education background, I was very new to educational research when starting in the Flynn Research Group as I previously conducted wet-lab photochemistry for my Honours Thesis. Therefore, it took me time to get situated with educational research methods as well as ST and chemistry education literature. I conducted two iterations of an educator questionnaire to investigate educators' perspectives on ST (Figure 13), which was partially due to my learning curve, but I later learned this is a normal part of conducting research across all disciplines.

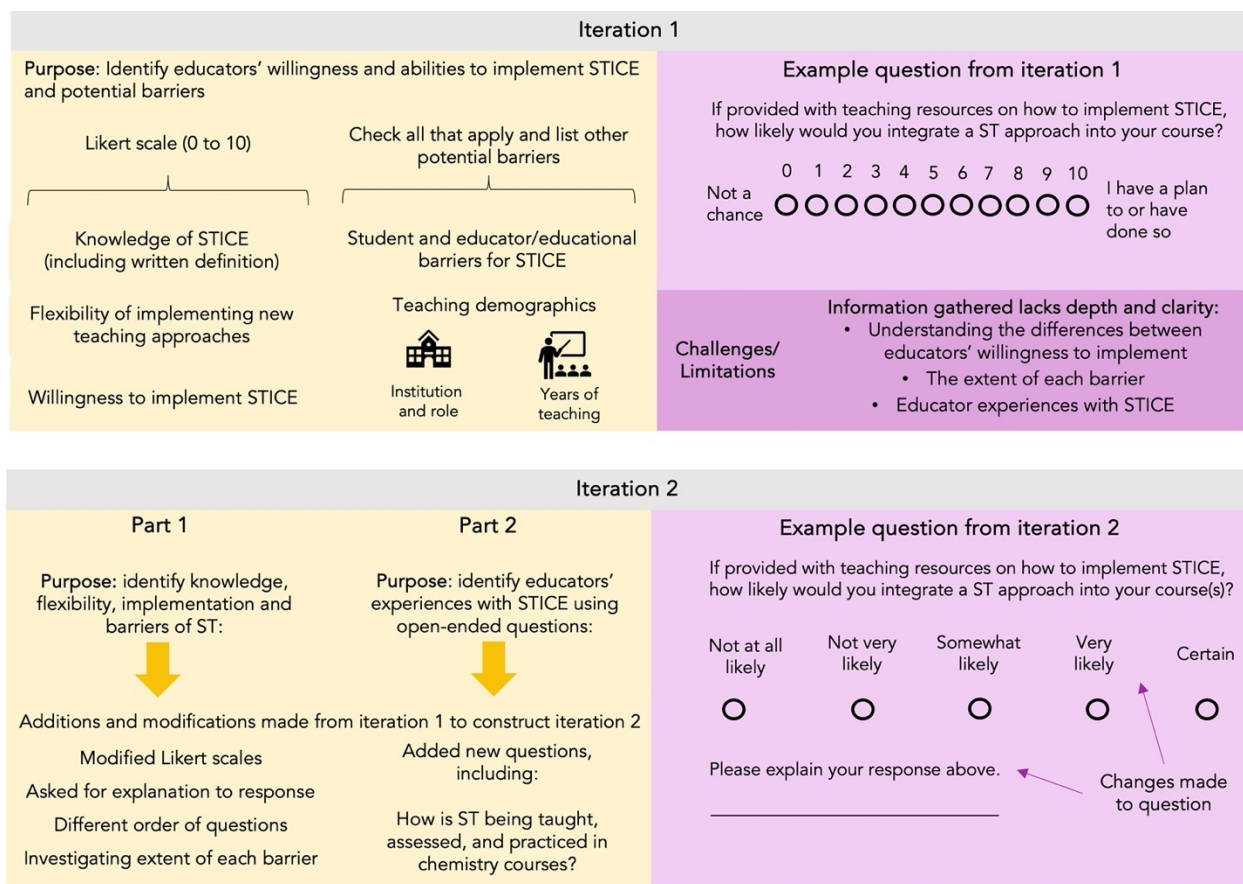


Figure 13. Two iterations for the development of an educator questionnaire.

After analyzing the data from forty-five chemistry educators in iteration 1, we found the information gathered lacked depth and clarity, identifying a few limitations of the questionnaire design. The challenges and limitations from the first iteration helped design the second iteration of the educator questionnaire which helped to increase the validity of our findings. For example, the Likert scale questions in iteration 1 had numerical scales without qualitative labels to indicate the meaning of each number. These Likert scale questions made it difficult to interpret responses during analysis. Therefore, in iteration 2, the Likert scales were changed using descriptive words and we asked for explanations of their Likert response. Additionally, from iteration 1, we identified which student and educator ST barriers were the most common among chemistry educators, but this question did not tell us the extent of each barrier. Thus, in iteration 2, we altered this question to investigate the extent of each ST barrier. Lastly, we realized iteration 1 collected little information about educators' experiences with ST in chemistry education, which may influence educators' perspectives toward ST. Therefore, we added a second part to the educator questionnaire that asked open-ended questions to better understand educators' experiences with ST in chemistry education. Additionally, the educator questionnaire was also provided

in French and recruitment text was also sent out through social media and other chemistry divisions' list serves to expand our recruitment and increase sample size. In the first iteration, we had only recruited chemistry educators from the Chemistry Education Division – Chemical Institute of Canada mail list and the international Chemical Education Research mailing list. Completing two iterations took more time and effort; however, I learned a lot from the process, and we were able to obtain richer data about educators' perspectives towards ST in chemistry.

I was very fortunate to mentor two undergraduate summer co-op students, Kathryn Bruyere and Haylee Lee, who helped with the initial qualitative and quantitative analyses of the findings from this study. The three of us identified key findings from the data; however, Dr. Alison Flynn prompted me to think bigger picture across the findings which led to overarching themes within the data. At this point, I became more confident with my qualitative analysis skills. This study led to my first manuscript. Since I do not consider myself a strong writer and given that formal writing was not taught or assessed in my undergraduate degree, Dr. Alison Flynn's constructive feedback, evidence-based writing strategies, and patience helped me develop more confidence in my writing abilities throughout my degree. Helping me achieve my writing goal is one aspect of her mentorship I am very grateful for during my PhD. I am also very thankful for the guidance and support provided by Dr. Alison Flynn, Dr. Peter Mahaffy (our collaborator on the ST project), and the Flynn Research Group who helped me identify some of the limitations from the first iteration of the educator questionnaire and provided valuable feedback when constructing and analyzing the second iteration. The collaborative effort of this team led to an outcome that was remarkable.

From iteration 2, we collected fifty-six participants' responses from 10 different countries, which is important for understanding how educators are thinking about ST globally. We delved deep into the findings through a manuscript we published in the *Journal of Chemical Education*, which has received over 1050 views and has been used to guide additional efforts on educators' perspectives in chemistry education.

2.2 References for introduction

- (1) Lund, T. J.; Stains, M. The Importance of Context: An Exploration of Factors Influencing the Adoption of Student-Centered Teaching among Chemistry, Biology, and Physics Faculty. *Int. J. STEM Educ.* **2015**, 2 (1), 13. <https://doi.org/10.1186/s40594-015-0026-8>.
- (2) Stains, M.; Harshman, J.; Barker, M. K.; Chasteen, S. V.; Cole, R.; DeChenne-Peters, S. E.; Eagan, M. K.; Esson, J. M.; Knight, J. K.; Laski, F. A.; Levis-Fitzgerald, M.; Lee, C. J.; Lo, S. M.; McDonnell, L. M.;

- McKay, T. A.; Michelotti, N.; Musgrove, A.; Palmer, M. S.; Plank, K. M.; Rodela, T. M.; Sanders, E. R.; Schimpf, N. G.; Schulte, P. M.; Smith, M. K.; Stetzer, M.; Van Valkenburgh, B.; Vinson, E.; Weir, L. K.; Wendel, P. J.; Wheeler, L. B.; Young, A. M. Anatomy of STEM Teaching in North American Universities. *Science* **2018**, *359* (6383), 1468–1470. <https://doi.org/10.1126/science.aap8892>.
- (3) 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>.
- (4) Delaney, S.; Ferguson, J. P.; Schultz, M. Exploring Opportunities to Incorporate Systems Thinking into Secondary and Tertiary Chemistry Education through Practitioner Perspectives. *Int. J. Sci. Educ.* **2021**, *43* (16), 2618–2639. <https://doi.org/10.1080/09500693.2021.1980631>.
- (5) 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>.

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Investigating Educators' Perspectives toward Systems Thinking in Chemistry Education from International Contexts

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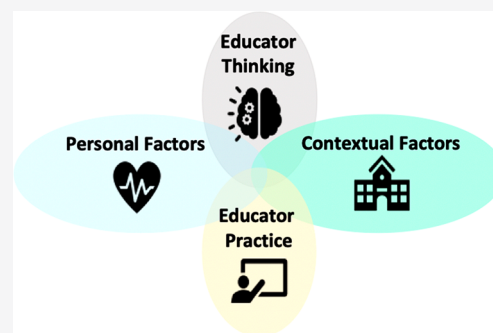


Supporting Information

ABSTRACT: Systems thinking in chemistry education (STICE) has been proposed as an approach that could better equip students with abilities to connect their chemistry knowledge with other disciplines and with the skills needed to tackle complex global issues. However, educational change in chemistry is a complex effort that involves many interconnected factors that enable or hinder chemistry educators' adoption of new pedagogical approaches. Using an adapted version of the Teacher-Centered Systemic Reform (TCSR) model, we investigated factors that connect with chemistry educators' willingness and ability to implement a STICE approach in their courses. We surveyed a group of 56 secondary and postsecondary chemistry educators from ten different countries, to capture chemistry educators' perspectives toward a STICE approach. Through thematic analysis of responses, we identified four key themes as follows. Theme 1:

Educators' willingness and ability to implement STICE is influenced by their knowledge, beliefs, experiences, contextual and personal factors; Theme 2: Educators report experiences with aspects of STICE without knowing or specifically calling it ST; Theme 3: Some educators implement limited aspects of STICE when teaching chemistry in context; and Theme 4: The ratings of barriers can guide priorities for educational change efforts. This paper discusses specific aspects of the reform model that experts and administrators can address to reduce barriers to implement and engage with STICE. We also highlight future chemistry education research that is needed to explore specific aspects of educators' perspectives and STICE more broadly.

KEYWORDS: Chemical Education Research, Systems Thinking, Transfer, Qualitative Analysis, General Public, First-Year Undergraduate, Second-Year Undergraduate, Upper-Division Undergraduate, Curriculum



INTRODUCTION

Chemistry is critically involved in tackling complex challenges, such as those prioritized with the United Nations' Sustainable Development Goals (SDGs),^{1,2} which include climate change, affordable and clean energy, and good health.^{3–6} The 17 SDGs provide a framework for developing a sustainable planetary society by the target date, 2030, and require a holistic understanding of the interactions involving chemistry and connections to other disciplines.^{1,7,8} However, current approaches in chemistry education often lack the connections to other disciplines and global issues, particularly in large enrollment courses and on assessments.⁹ In many courses, facts are learned in silos where emphasis is placed upon detailed descriptions of fundamental, yet narrow, principles.^{10–12} Consequently, learning discrete, unconnected facts out of context limits learners' abilities to apply knowledge and skills in new contexts, such as understanding how chemical processes impact and are impacted by societal, economic, political, and environmental factors.^{3,10,12}

Building the capacity to achieve the SDGs and expectations of a 21st century workplace requires evidence-based approaches to postsecondary STEM education. Recent compelling international calls have been made to reorient

chemistry education using a systems thinking (ST) approach.⁹ ST has been proposed by chemistry educators as part of an approach to chemistry education that could bridge the disciplines and more effectively educate the next generation of scientists and prepare citizens for their roles on a rapidly changing planet.^{2,6}

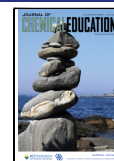
Research on ST in other disciplines suggests there would be strong benefits for introducing systems thinking in chemistry education (STICE).^{13–17} However, rigorous educational research is needed to determine effects and impacts of STICE approaches.³ Moreover, educators would need to be willing, able, supported, and rewarded in making such profound changes to their courses.

While there may be benefits and opportunities from implementing STICE, there are also challenges and risks. If ST approaches are to be successfully integrated in chemistry

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education, educators' perspectives and contexts must be deeply understood so that their needs can be addressed. These aspects play critical roles in educators' decisions to advance instructional change, based on extensive research at the secondary and postsecondary levels (e.g., educators' ability to make course or program changes).^{18–20} Additionally, beliefs held by educators about teaching and learning and their own abilities influence their adoption of new pedagogy.^{21,22}

The lack of an operational definition of ST remains a challenge for its practical implementation in the chemistry education community. An IUPAC project called Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+) was launched to bring international attention and credibility to catalyze change and increase support for STICE.^{23,24} To date, working group 2 of the IUPAC STCS 2030+ project informally proposed the following operational definitions of systems-related concepts for implementation in chemistry education:²⁴

Systems thinking is the ability to understand and interpret complex problems (ref 25, 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 30, p 39). 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:^{23,26–29} 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).

This operational definition of systems-related concepts will be useful for maintaining consistency in the implementation, assessment, curriculum development, and research of systems thinking in chemistry education (STICE).

The Special Issue of the Journal of Chemistry Education "Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry" was a great starting point for providing a range of STICE resources (e.g., ST activities, demonstrations, laboratory experiments, technology-based learning resources).³¹ However, there are still limited ST teaching resources available among chemistry courses and limited methods for assessing or measuring ST competencies.^{3,25,32} None of these assessment methods have been validated and are not designed to be easily implemented in large classes, such as first year chemistry university courses.³ Beyond individual teaching resources at the course level, ST approaches in chemistry courses need to be aligned with curricula at institutional and national levels, and international education standards to achieve widespread adoption of STICE.^{33–35} However, ST is not the only approach for learning and teaching chemistry concepts, and more research is needed to identify what areas of chemistry are most appropriate for a ST approach.³ The present study is designed to investigate educators' perspectives about and knowledge of STICE, as to date, little is known about this critical group's perspectives.

Goals and Research Questions

The overarching goal of this project is to investigate and prioritize the current actions and future research needed to

help chemistry educators practically enact ST approaches. In this study we addressed the following research question: **What are educators' knowledge about and perspectives on implementing STICE?**

To conduct this study, we created and released a questionnaire to capture chemistry educators' perspectives globally toward a STICE approach. The findings from this questionnaire have two purposes: (1) to guide the creation of potential solutions to overcome educator barriers to determine the feasibility of the ST approach in different contexts and (2) inform future actions to address educator systemic change and additional CER that is needed to increase efforts of chemistry educators implementing STICE.

Theoretical Framework

Several contemporary empirical models on instructional practices have been developed to highlight the influence of educators' beliefs on their teaching practices.^{19,36} We adapted the Teacher-Centered Systemic Reform (TCSR) Model to address the implementation of ST by chemistry educators.²¹ This model positions educators at the center of educational reform by placing an emphasis on educators' thinking and interconnecting their knowledge and beliefs across three domains, which are (1) contextual factors, (2) personal factors, and (3) educator experience (Figure 1). The domains highlight the robust link between educators' beliefs and willingness to make changes to their teaching. Additionally, this model explains the multifaceted systemic nature of education as each domain is aligned with potential STICE educator and educational barriers. Since our research focuses on thoroughly understanding educators' perspectives and contexts, we identified educators' current ST barriers and used the TCSR model to understand the factors involved. Highlighting these factors brings attention to increased efforts needed to effectively address these barriers. If educators are to enact a ST approach, educational reform efforts need to consider the interconnectedness between the domains in the model.

METHODS

Instrument for Data Collection

We developed a three-part questionnaire to capture educators' perspectives. Part 1 of the questionnaire used a combination of Likert-scale questions and open-ended questions aimed to identify chemistry educators' current knowledge of STICE, identify how much flexibility educators have for implementing new teaching approaches (e.g., flexibility related to structural constraints, policies imposed by institution, departmental expectations), identify how much educators are willing to implement a ST approach, and determine potential student and educator barriers that may prevent educators from practically enacting this approach. We evaluated 11 educator/educational barriers aligned with the four domains of the TCSR model that have been previously proposed by educators (Figure 1).

Part 2 investigated participants' experiences with STICE using open ended questions. We provided a definition and five essential characteristics of STICE.^{8,10,23} These essential characteristics include the following: (1) recognizing a system as a whole, not just as a collection of parts, (2) examining the relationships between the parts of a system and how those interconnections lead to cyclic system behaviors, (3) identifying variables that cause system behaviors, including

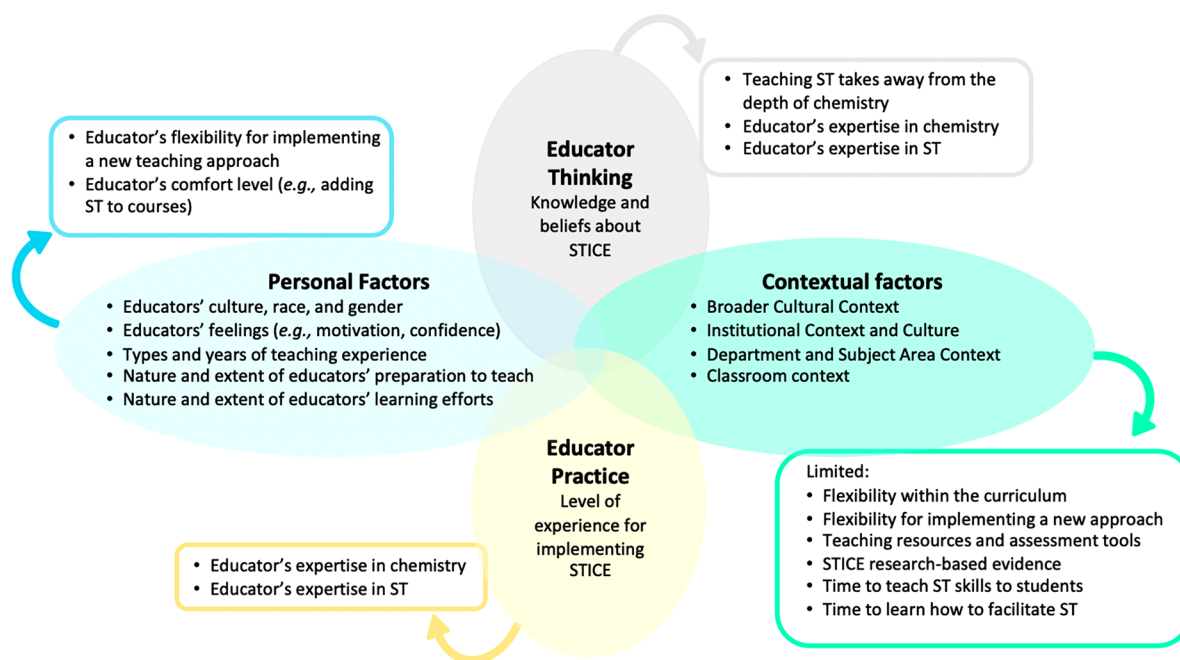


Figure 1. A STICE perspective of the Teacher-Centered Systemic Reform (TCSR) model (opaque ovals), aligned with potential STICE educator and educational barriers (outlined boxes) that we probed in the study.

unique system-level emergent behaviors, (4) examining how system behaviors change over time, and (5) identifying how knowledge of chemistry connects to social, technological, economic, and environmental systems at work in our world (multidisciplinary).²³

Subsequently, the questionnaire asked educators to choose a category that best represented their experience with STICE. The options include the following: (1) I have not implemented ST into the course(s) I teach, (2) I have implemented ST into the course(s) I teach, or (3) I have implemented ST principles into the course(s) I teach. We designed Categories 2 and 3 to distinguish educators who explicitly (2) and implicitly (3) implement STICE. These categories guided participants to answer several open-ended questions related to their experience and perspectives on STICE based on the category chosen, requiring a written response. The questionnaire further asked educators who had experience with STICE to identify which aspects of STICE they incorporate into their courses. Therefore, we explored how STICE is being taught, practiced, and assessed in their courses, when they started implementing STICE into their course(s), resources they use, resources they need, and how they overcome barriers associated with ST.

Part 3 of the questionnaire included demographic questions related to teaching (e.g., institution at which they teach, educational role, years of teaching, courses they teach), gender, culture, and race (details in [Supporting Information](#)).

Participants

Fifty-six chemistry educators from ten different countries participated; they represented a combination of high school and postsecondary educators who identified as a woman, man, or nonbinary, and teach a range of chemistry courses. This research received approval from the University of Ottawa's Office of Research Ethics and Integrity (#H03-20-5585).

Data Analysis

Qualitative analysis first began by reviewing the open-ended response data thoroughly and highlighting significant features

of the data related to the research question. Each question involved open coding using NVivo 12 to ensure we did not miss any information, and that we coded all content as effectively and as accurately as possible.³⁷ Next, we sorted the list of codes and organized into categories. Throughout the coding process, we engaged in constant comparative analysis and critically debated the presence/absence of codes.³⁸ We refined the codes and grouped the codes multiple times throughout the coding process until no new codes were generated. Then, we synthesized the categories that were similar in nature and derived themes depending on how they related to the research question. Authors also considered the prior knowledge of ST and noted it throughout the analysis. Writing memos helped communicate the coding process and emerging patterns, categories, and themes in the data among the researchers.³⁸ The record of memos helped ensure confirmability and dependability of the analysis.³⁹ Overall, we analyzed the data using thematic analysis.^{40,41} We addressed the validity of the findings using well-established methods (details in the [Supporting Information](#)).^{42,43}

We carried out a quantitative analysis for the Likert scale questions related to knowledge, flexibility, willingness to implement STICE, years of teaching experience, experience with STICE, and the student and educator/educational barriers questions. A Spearman's rank correlation test determined any relationships among these factors.⁴⁴ We conducted Kruskal–Wallis tests to determine whether there was a statistically significant difference in the average extent of educator/educational barriers between the experience groups. In the following sections, we describe the main findings, starting with the key themes that emerged.

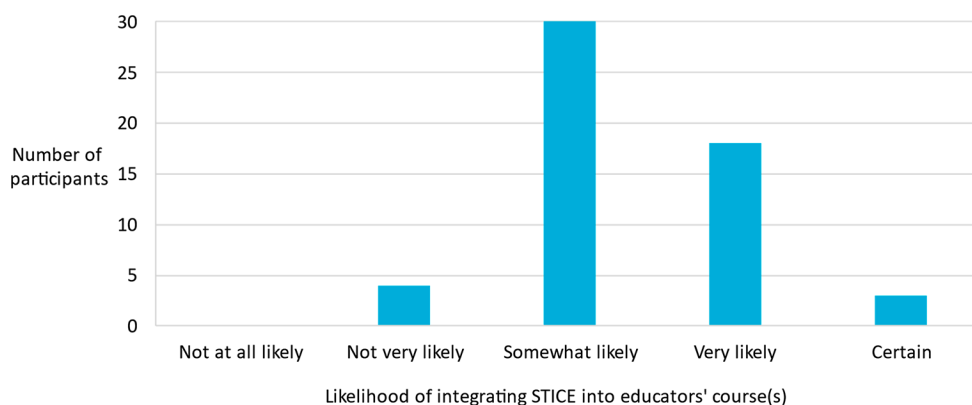


Figure 2. Educators' likelihood of integrating STICE into their course(s) ($N = 55$).

RESULTS AND DISCUSSION

Theme 1: Knowledge, Experience, Beliefs, Personal and Contextual Factors Influenced Educators' Willingness to Implement STICE

Most participants (93%) gave a neutral to positive response about their willingness to integrate STICE into their course(s) (Figure 2). A full 55% of these participants were only somewhat likely to integrate STICE into their course(s), making us suspect that barriers or beliefs were affecting their ability or desire to implement STICE. No participants chose "not at all likely", which is a positive finding for the future of STICE adoption.

Five categories of factors influenced educators' willingness to implement STICE: knowledge of STICE, experience with STICE, beliefs about STICE, and contextual and personal factors (Figure 3). Contextual factors had the largest influence on educators' willingness to implement STICE. Participants (55%) indicated that their willingness would depend on availability of teaching resources, curriculum coverage, research-based evidence, and time constraints to learn and implement STICE (Figure 3). Time and curriculum coverage limitations have also been recently emphasized as main limitations to implement STICE by other researchers, highlighting the substantial need for change in these areas.^{45,46}

For successful adoption of STICE, there needs to be increased efforts for educational change at the departmental, institutional, and administrative levels (e.g., departmental STICE training, institutional policy changes, restructuring of curriculum, and assessments) as participants most frequently reported those four contextual factors as potential barriers to implement STICE. Reward and promotion practices have also been concrete ways in which institutions incentivize educators' choices in their educational efforts.⁴⁷

Educators were likely to implement STICE due to their experience, beliefs, and feelings toward STICE. Seven participants mentioned they have created or are creating a plan to implement STICE into their courses or they are already implementing STICE. These planned or existing experiences correspond to the high willingness to implement responses in the Likert scale question (Figure 2).

Educators had two common categories of beliefs about why they would be willing to implement STICE: (1) ST helps with student skill and knowledge development and (2) STICE is important for helping shape the future of chemistry and society (Table S2). When participants were asked, "Do you think it is important for educators to implement a ST approach to their

courses? Why or Why not?", the same beliefs emerged with the addition of another common belief that ST increases student engagement for learning chemistry (Table S2). All educators who had one of these beliefs reported having experience with implementing STICE, which suggests that the importance of STICE and its benefits may emerge through their teaching experiences. Support of these findings are represented by recent publications from other STICE researchers who have investigated chemistry educator perspectives and have obtained similar results.^{45,48} While these findings represent positive perspectives about STICE, not all educators' beliefs were positive about the importance of implementing STICE. For example, some educators believe there are issues with implementing STICE due to curriculum requirements and time constraints, both aligning with the contextual factors previously identified.

Educators also believe that there is a certain course level that is appropriate for implementing STICE. Educators gave two main reasons: limitations of students' skills and knowledge levels and the curricular change required by ST. Specifically, some educators believe it would be difficult to implement STICE at an institution without every educator doing it. If an educator was the only one to implement STICE into their course within their department, they were concerned about how implementing STICE would affect other colleagues who depend on the prerequisite knowledge for subsequent courses they teach and how it would impact students learning in upper-level courses. Such a situation commonly arises in first year chemistry courses (i.e., general chemistry).

To better understand educators' beliefs, future research is needed to (1) investigate when ST should be implemented in students' educational careers, along with the specific benefits and challenges it might provide for students at each course level and (2) determine if all educators are required to implement STICE in a program or at an institution for it to be effective.

Educators' feelings (personal factors) for trying new teaching approaches corresponded to higher willingness to implement STICE. Some educators were interested in learning about new teaching approaches ($n = 6$) and were willing to try new approaches ($n = 3$). On the other hand, two educators mentioned they would likely integrate STICE if the approach aligned with their teaching values or current teaching approach. This finding aligns with aspects of STICE that educators want to learn more about (e.g., how STICE can be integrated in current teaching approaches) (Figure S4).⁸⁵

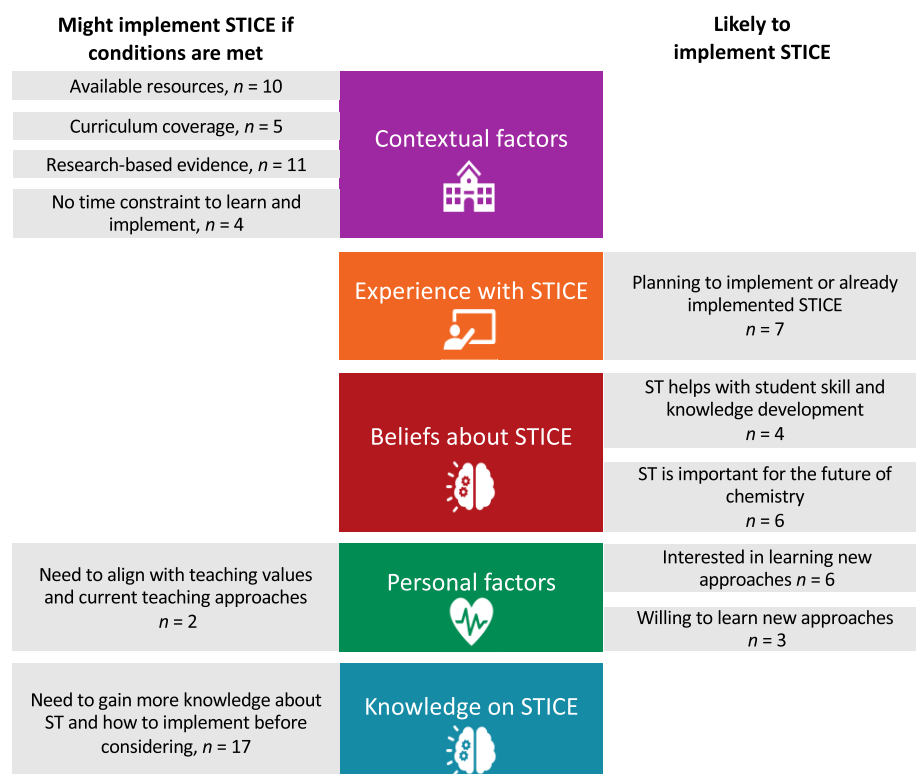


Figure 3. Factors that influence educators' willingness to implement STICE.

The educators' role—another personal factor—had an influence on educators' ability to implement STICE ($n = 9$) (Table S5). Generally, educators who were the only instructor for their course reported to have more flexibility for implementing new approaches compared to educators who taught one section of a large enrollment course or cotaught courses. This finding suggests that certain teaching contexts and roles may be viewed as a greater barrier to implement new approaches due to the collaborative nature of the job and the requirement that all instructors teaching that course may need to have similar views on how they plan on teach the content. Future research is needed to investigate how STICE can be effectively implemented in different teaching contexts that require educators to have similar perspectives.

Social pressure is an implicit and hidden factor that also emerged from analysis, affecting educators' flexibility to implement new teaching approaches (Table S5). Specifically, social pressure from colleagues was reported to restrict educators' freedom to implement new approaches. Research on change in universities and colleges has demonstrated that systemic change occurs when a concerted effort is made by senior leaders (i.e., Deans, Department Chairs) in an institution to motivate their colleagues and obtain buy-in for change.^{49,50}

In comparison to other predictor variables that were investigated through the questionnaire (i.e., flexibility, experience with STICE), knowledge of STICE was the only factor that showed a correlation with educators' willingness to implement, based on Spearman's rank correlation test, $r_s = 0.457$, $p < 0.001$, bias corrected accelerated 95% confidence interval [0.184, 0.674], a medium effect size (Table S3).⁵¹

Seventeen participants indicated they would consider implementing STICE if they had more knowledge about STICE and/or how to implement STICE, which is consistent

with educators' reported low level of knowledge of STICE (Figure S2). Most participants were interested in learning ways to effectively implement and integrate STICE in a course or classroom and how to integrate STICE with other teaching pedagogies. Additionally, educators wanted specific examples and applications of STICE being implemented and assessed by chemistry instructors along with teaching and learning resources and assessment tools and examples to integrate STICE into their course(s). Assessment tools and teaching resources were the most frequently reported resources that educators would need to implement STICE. On the basis of the efforts to date that have aimed to infuse ST approaches in chemistry education, our results indicate there is a need for professional development opportunities focused on building educators' understanding of ST perspectives and demonstrating how to facilitate and integrate ST approaches to chemistry courses.³

Experts and policy makers may find the adoption of educational change models to be helpful in guiding future direction of the STICE.^{18,49,52} Specifically, in order for educators to change their willingness to adopt STICE approaches, efforts need to be made to increase educators' knowledge of STICE, minimize contextual factors primarily at the administrative level, and help align ST approaches with educators' values and current teaching approaches (personal factors).

Theme 2: Educators Report Having Experience with STICE without Knowing or Specifically Calling it ST

Comparing educators' definitions and level of knowledge of STICE with their chosen category of experience, we found that educators may have experience with STICE without knowing about STICE or calling it systems thinking. In arriving at this conclusion, we first confirmed that chemistry educators' self-

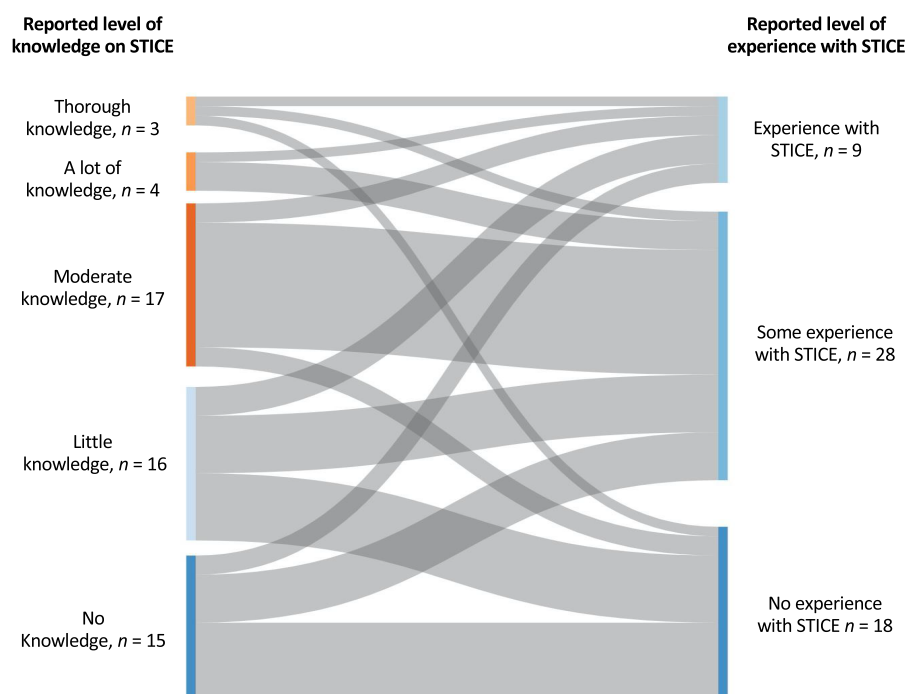


Figure 4. Educators' self-reported knowledge of STICE before receiving a STICE definition and educators perceived experience after receiving STICE definition.

reported level of knowledge about STICE was consistent with their definitions (from part 1 of the questionnaire). For example, over half of the participants indicated they had little to no knowledge of STICE; therefore, not surprisingly, 18 of these participants only indicated one characteristic of ST in their definition (Figure S5). The six characteristics of STICE that emerged from educators definitions were as follows: (1) ST is a holistic approach/involves big picture thinking, (2) ST involves interconnections between concepts/topics/disciplines, (3) ST is an approach that applies chemistry to other contexts, (4) ST involves looking at variables that cause behaviors and outcomes, (5) ST involves understanding and analyzing complex systems, and (6) STICE recognizes that systems are embedded in chemistry.

The second part of the analysis compared educators' reported level of knowledge with their level of experience, which they self-reported after being provided with a definition of STICE. Fifteen participants who reported little or no knowledge about STICE had no experience with implementing STICE, while 16 participants within both knowledge groups (no or little knowledge) reported they had implemented STICE or implemented ST principles into the course(s) they teach (Figure 4). Figure 4 shows one participant self-reported thorough knowledge about STICE and no experience with implementing STICE. This participant may have had no experience with STICE due to their current role as a graduate student, which may have limited their ability to implement STICE into a course.

Considering that over half of the participants reported they had little to no knowledge about STICE, participants may not have known the extent of ST or never heard of ST but have been implicitly embedding ST principles and characteristics into their teaching. For example, one participant recognized they implement ST in one of their courses but realized they had never called it ST:

Although I've never called it systems thinking (or thought of it as something different), it seems to be what I've been doing in this one course.

If chemistry educators were to become more knowledgeable about STICE, they will need to understand how to make changes to their current teaching approaches to better encompass a ST approach. Future research on STICE will be needed to determine the extent of adaptation made to chemistry educators current teaching pedagogy when ST approaches are integrated with the curriculum and program standards. Therefore, STICE educational change may be easier to achieve than expected as chemistry educators may not need to make huge modifications to their current teaching approach due the overlap of ST characteristics.

Theme 3: Some Chemistry Educators Implement Limited Aspects of STICE When Teaching Chemistry in Context

Our findings show that some educators primarily implement one aspect of STICE (i.e., teaching chemistry in context) which is considered the main similarity between STICE and context-based approaches (Figure 5). While ST and context-based pedagogies share characteristics, there are important differences (Figure 5).²³ Context-based learning has been shown to have benefits to chemistry education;^{53–57} however, encompassing more aspects of ST in the field of chemistry education may offer other distinct benefits for student learning as they are able to engage in more higher-order thinking skills, previously shown in other disciplines.

We arrived at this conclusion by looking at how educators described how they implemented or how they planned to implement ST into their course(s). Four categories emerged from participants' responses on how they implemented or planned to implement ST: (1) 54% emphasized specific characteristics of STICE (e.g., focus on holism/bigger picture when teaching chemistry, teach causal behaviors of a system, and teach chemistry contexts within real-world context), (2)

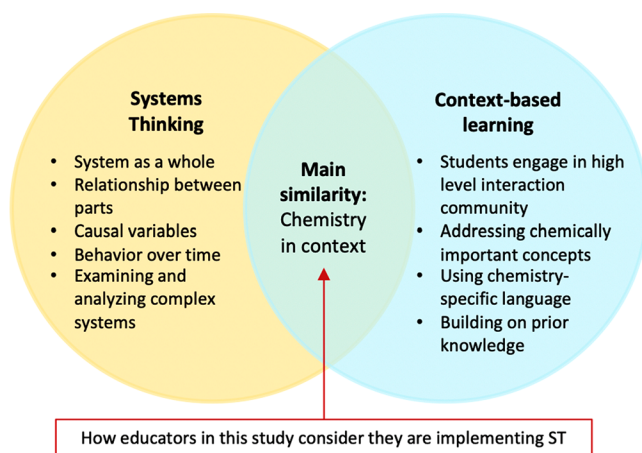


Figure 5. Similarities and differences of system thinking approaches and context-based learning adapted with permission from ref 27. Copyright (2020) American Chemical Society.

18% gave general ways to incorporate STICE into learning (e.g., STEM projects, curriculum, designed and applied activities), (3) 14% use a different teaching approach to incorporate aspects of ST, and (4) 22% do not explicitly state how they implement STICE.

Thematic analysis revealed that educators primarily implement aspects of STICE characteristics in the following ways: (1) teaching chemistry with emphasis on societal and/or environmental context, (2) incorporating real world connections and applications of chemistry into their teaching, or (3) giving an example how connections to real life applications are taught in their chemistry course(s). These ways are aspects of STICE, but miss some important aspects needed to truly achieve a STICE approach (Figure 5).

Additionally, participants' responses mentioned they incorporate real world connections of chemistry and indicated they include essential characteristics of STICE (e.g., recognizing a

system as a whole, not just as a collection of parts, identifying variables that cause system behaviors) into their course(s), but they did not explicitly **describe or explain** how they incorporate these essential STICE characteristics into their teaching. Therefore, there is no concrete evidence that shows how educators implement a STICE approach. This result leads to the question: How do we know if educators are using a context-based approach rather than a STICE approach?

These findings show that efforts are needed to bridge knowledge of STICE and implementing STICE in educators' teaching. This knowledge gap may be addressed by clearly defining the criteria required to integrate STICE (e.g., what is required of the learner and instructor) as currently it remains unclear in the literature due to the vast range of definitions of STICE.⁴⁸ Results of these efforts will help educators distinguish similar teaching approaches (e.g., context-based, problem-based, and inquiry-based learning, life cycle analysis, and multivariate reasoning) from STICE approaches, which will allow educators to identify the specific aspect of their current teaching that would need to be adapted to adopt a ST approach. Educators will then be able to better assess their feasibility and flexibility of integrating this approach to their course(s).

Theme 4: Rating of Barriers Can Guide Priorities for Educational Change Efforts

Educators reported the extent of educator and educational barriers for implementing STICE into their course(s) (Figure 6, Table S8). The weighted averages of each barrier show that educators' expertise on ST and barriers related to limited time and resources (i.e., limited time to learn and teach STICE, limited teaching resources and assessments) are perceived to have the greatest extent as barriers to STICE. Educators' expertise reported as a larger barrier indicates participants knowledge and/or experience may be a predictor for chemistry educators' willingness to implement STICE. Due to our

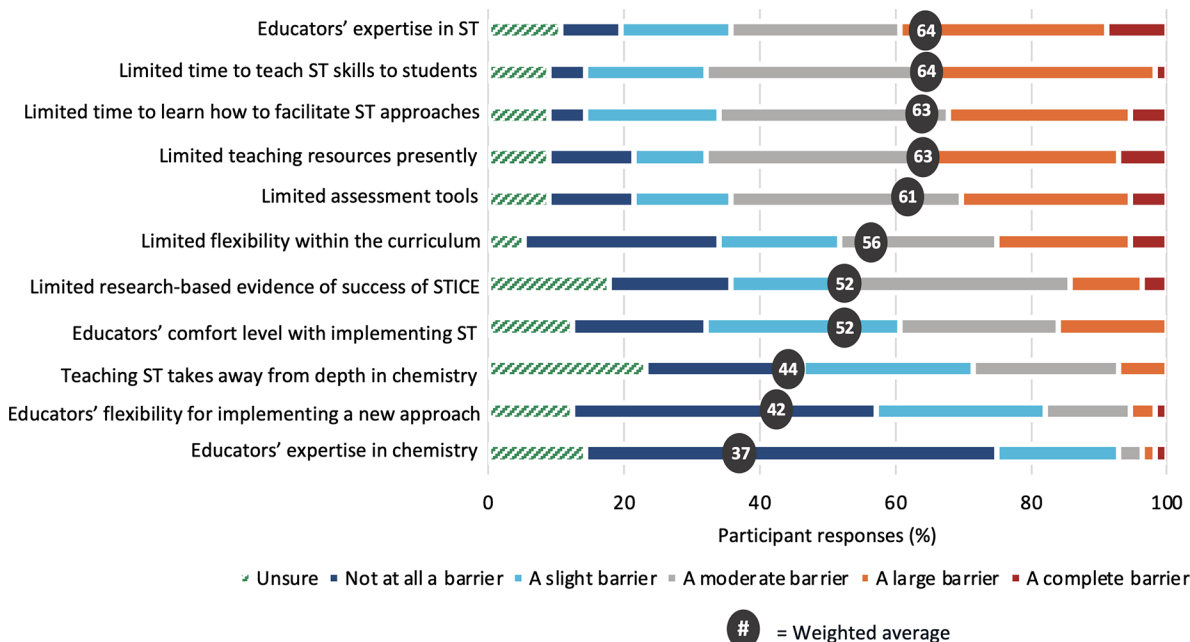


Figure 6. Extent of educator and educational barriers for STICE self-reported by chemistry educators. Circled values represent weighted averages of the extent of each barrier; these are approximations as the data are categorical.⁵⁸

limited sample size, we were unable to proceed with conducting a regression to test this hypothesis.

Additionally, there is a need for these types of resources to be developed for a range of chemistry courses. One participant who creates their own learning activities stated they “spend a lot of time (and some internal funding) to develop new learning resources and learning activities”. Minimizing barriers related to time to teach and learn STICE can be achieved with two key actions: (1) more openly available resources and (2) more effort to support the transition for educators to adopt this approach (e.g., professional development workshop and activities, textbooks, embedding STICE within curricula or guides to implementation). These actions will allow chemistry educators to spend less time trying to learn and develop their own resources, decreasing the extent of this barrier toward implementing STICE. To date, there have been several webinars on STICE;⁵⁹ however, educators reported they want hands-on STICE experiences (Table S6).

Limited evidence-based research is considered a moderate barrier, which is understandable since little evidence is currently available about the effectiveness of the STICE approach.³ At the same time, chemistry educators may not know the extent of STICE literature available.

On the other hand, educators’ flexibility for implementing STICE and educators’ expertise in chemistry were mostly perceived as not being a barrier or slightly a barrier for enacting a STICE approach to their course(s). The reason flexibility for implementing STICE may be perceived as less of a barrier is because participants have a high level of flexibility for implementing new teaching approaches in general (Figure S1).

Lastly, participants were most unsure about the lack of depth in chemistry as a barrier to STICE. This barrier relates to the perception that implementing STICE would come at the expense of depth of coverage of chemistry content. These educators might not have a clear understanding of how STICE might impact the depth of coverage of chemistry content due to the lack of educators’ knowledge about STICE.

We hypothesized educators’ level of experience with implementing STICE may influence the extent of each barrier. Two of the 11 educator/educational barriers showed a significant relationship with educators’ experience with STICE. These educator barriers were as follows: limited time to teach ST skills to students ($H(2) = 7.504$, $p = 0.023$, $E_R^2 = 0.1501$, medium effect size) and educators’ comfort level with implementing STICE ($H(2) = 6.511$, $p = 0.039$, $E_R^2 = 0.1356$, small to medium effect size) (Figure S9). In other words, once participants have experience with STICE, they may perceive barriers to have less of an impact than participants who have no experience with STICE. Accordingly, helping educators gain even some experience in STICE could propel further change.

Educational change models will likely help overcome these barriers to implementing STICE. A focus on educating educators about STICE may help educators understand how ST might impact the depth of content coverage in chemistry and might influence their willingness to implement a STICE approach. Addressing contextual factors will allow educators to have teaching resources and assessment tools to be able to implement STICE and may increase their willingness to implement if STICE is integrated within curricula and evidence-based research shows it to be effective in specific learning contexts. Overall, efforts made toward educators’ knowledge and contextual factors may result in more concerted

efforts by chemistry educators to implement ST into their teaching practice.

CONCLUSION

To overcome educational challenges related to implementing a STICE approach, educators’ perspectives and contexts need to be thoroughly understood in order to effectively address their needs. Educational change models can be adopted to help understand the interconnectedness of educator barriers and factors involved and guide future actions to address educator systemic change. We investigated chemistry educators’ knowledge of and perspectives about STICE to inform departmental, institutional, and administrative initiatives to implement STICE.

We found that educators’ knowledge (i.e., low level of knowledge about STICE), contextual factors (i.e., willingness depends on availability of teaching resources, curriculum coverage, research-based evidence, and time constraints to learn and implement STICE), and personal factors (i.e., STICE approach needs to align with their teaching values or current teaching approach) all negatively influenced educators’ willingness to implement a STICE approach. Therefore, efforts of change need to be made toward these three areas of the educator change model, to increase educators’ willingness to adopt STICE approaches.

Educators reported experiences with STICE without knowing or specifically calling it ST; however, generally educators only considered that they implemented STICE by teaching chemistry concepts and topics in context. Therefore, efforts need to be made to clearly distinguish the requirements of a STICE approach for the instructor and learner and how educators’ current teaching approaches (e.g., context-based learning) can be adapted to encompass the requirements of STICE.

Lastly, participants’ ratings indicated that some educational barriers related to educators’ knowledge and contextual factors require more attention for change than other barriers.

Our results support the value of the TCSR model as a framework to develop instructional change for STICE, and it may empower educational administrators and policy makers to consider the multifaceted nature of change when working with chemistry educators.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemeduc.2c00138>.

Details about the methods, participants, data analysis, and themes as well as the code books (e.g., themes, categories, description of categories, and representative quotes) for this study (PDF) (DOCX)

Educator perspectives questionnaire (PDF) (DOCX)

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Author Contributions

ARS and ABF conceived the project and designed the methods, in collaboration with PGM. ARS collected the data. ARS analyzed the data with contributions from KB (qualitative data analysis) and HL (quantitative data analysis). All authors contributed to discussing results and forming conclusions. ARS wrote the first draft of the manuscript. ABF and PGM edited and revised the manuscript.

Notes

The authors declare no competing financial interest.

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REFERENCES

- (1) United Nations Sustainable Development Goals. <http://sustainabledevelopment.un.org/> (accessed on February 23, 2022).
- (2) Pazicni, S.; Flynn, A. B. Systems Thinking in Chemistry Education: Theoretical Challenges and Opportunities. *J. Chem. Educ.* **2019**, *96* (12), 2752–2763.
- (3) 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.
- (4) Jerrentrup, R. The Effects of the Financial Crisis on the Future of the Chemical Industry. *J. Bus. Chem.* **2009**, *6* (1), 3–6.
- (5) Jun, Y. G. *Friend or Enemy—Chemistry in Crisis (Chinese Ed.)*; Tianjin People's Publishing House, 2011.
- (6) Matlin, S. A.; Mehta, G.; Hopf, H.; Krief, A. One-World Chemistry and Systems Thinking. *Nat. Chem.* **2016**, *8* (5), 393–398.
- (7) Anastas, P. T.; Zimmerman, J. B. The United Nations Sustainability Goals: How Can Sustainable Chemistry Contribute? *Curr. Opin. Green Sustain. Chem.* **2018**, *13*, 150–153.
- (8) 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.
- (9) Mahaffy, P. G.; Krief, A.; Hopf, H.; Mehta, G.; Matlin, S. A. Reorienting Chemistry Education through Systems Thinking. *Nat. Rev. Chem.* **2018**, *2* (4), 126.
- (10) Orgill, M.; York, S.; MacKellar, J. Introduction to Systems Thinking for the Chemistry Education Community. *J. Chem. Educ.* **2019**, *96* (12), 2720–2729.
- (11) Alien, R. T. Reductionism in Education. *Philos. Inq. Educ.* **1991**, *5* (1), 20–35.
- (12) Holme, T. A.; Hutchison, J. E. A Central Learning Outcome for the Central Science. *J. Chem. Educ.* **2018**, *95* (4), 499–501.
- (13) 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.
- (14) 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.
- (15) Frank, M. Engineering Systems Thinking and Systems Thinking. *Syst. Eng.* **2000**, *3* (3), 163–168.
- (16) 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.
- (17) 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.
- (18) Lund, T. J.; Stains, M. The Importance of Context: An Exploration of Factors Influencing the Adoption of Student-Centered Teaching among Chemistry, Biology, and Physics Faculty. *Int. J. STEM Educ.* **2015**, *2* (1), 13.
- (19) Gess-Newsome, J.; Southerland, S. A.; Johnston, A.; Woodbury, S. Educational Reform, Personal Practical Theories, and Dissatisfaction: The Anatomy of Change in College Science Teaching. *Am. Educ. Res. J.* **2003**, *40* (3), 731–767.
- (20) Stains, M.; Harshman, J.; Barker, M. K.; Chasteen, S. V.; Cole, R.; DeChenne-Peters, S. E.; Eagan, M. K.; Esson, J. M.; Knight, J. K.; Laski, F. A.; et al. Anatomy of STEM Teaching in North American Universities. *Science* (80-) **2018**, *359* (6383), 1468–1470.
- (21) Woodbury, S.; Gess-Newsome, J. Overcoming the Paradox of Change without Difference: A Model of Change in the Arena of Fundamental School Reform. *Educ. Policy* **2002**, *16* (5), 763–782.
- (22) Gibbons, R. E.; Villafañe, S. M.; Stains, M.; Murphy, K. L.; Raker, J. R. Beliefs about Learning and Enacted Instructional Practices: An Investigation in Postsecondary Chemistry Education. *J. Res. Sci. Teach.* **2018**, *55* (8), 1111–1133.
- (23) 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.
- (24) 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 on April 6, 2022).
- (25) 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.
- (26) 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.
- (27) 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.
- (28) 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.
- (29) Marton, F. Describing and Improving Learning. In *Learning Strategies and Learning Styles*; Springer Science+Business Media: New York, NY, 1988; pp 53–82.
- (30) Talanquer, V. Some Insights into Assessing Chemical Systems Thinking. *J. Chem. Educ.* **2019**, *96*, 2918.
- (31) 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.
- (32) Sabelli, N. H. Complexity, Technology, Science, and Education. *J. Learn. Sci.* **2006**, *15* (1), 5–9.

- (33) Aubrecht, K. B.; Dori, Y. J.; Holme, T. A.; Lavi, R.; Matlin, S. A.; Orgill, M.; Skaza-Acosta, H. Graphical Tools for Conceptualizing Systems Thinking in Chemistry Education. *J. Chem. Educ.* **2019**, 96 (12), 2888–2900.
- (34) Chiu, M.-H.; Mamlok-Naman, R.; Apotheker, J. Identifying Systems Thinking Components in the School Science Curricular Standards of Four Countries. *J. Chem. Educ.* **2019**, 96 (12), 2814–2824.
- (35) Elmgren, M.; Ho, F.; Åkesson, E.; Schmid, S.; Towns, M. Comparison and Evaluation of Learning Outcomes from an International Perspective: Development of a Best-Practice Process. *J. Chem. Educ.* **2015**, 92 (3), 427–432.
- (36) Clarke, D.; Hollingsworth, H. Elaborating a Model of Teacher Professional Growth. *Teaching and Teacher Education*, 18(8), 947–967. *Teach. Teach. Educ.* **2002**, 18, 947–967.
- (37) Williams, M.; Moser, T. The Art of Coding and Thematic Exploration in Qualitative Research. *Int. Manag. Rev.* **2019**, 15, 45.
- (38) Saldaña, J. *The Coding Manual for Qualitative Researchers*; Sage Publications Ltd., 2009.
- (39) Anney, V. N. Ensuring the Quality of the Findings of Qualitative Research: Looking at Trustworthiness Criteria. *Journal of Emerging Trends in Educational Research and Policy Studies (JETERAPS). Sci.* **2014**, 5, 272–281.
- (40) 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, 2003.
- (41) Boyatzis, R. E. *Transforming Qualitative Information: Thematic Analysis and Code Development*; Sage Publications, Inc.: Thousand Oaks, CA, 1998.
- (42) Lincoln, Y. S.; Guba, E. G.; Pilotta, J. J. *Naturalistic Inquiry*; Sage: Newbury Park, CA, 1985.
- (43) Creswell, J. W.; Miller, D. L. Determining Validity in Qualitative Inquiry. *Theory Pract.* **2000**, 39 (3), 124–130.
- (44) Field, A. *Discovering Statistics Using IBM SPSS Statistics*; Introducing Statistical Methods; SAGE Publications, 2013.
- (45) 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.
- (46) 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.
- (47) Fairweather, J. S. Beyond the Rhetoric: Trends in the Relative Value of Teaching and Research in Faculty Salaries. *J. Higher Educ.* **2005**, 76 (4), 401–422.
- (48) Delaney, S.; Ferguson, J. P.; Schultz, M. Exploring Opportunities to Incorporate Systems Thinking into Secondary and Tertiary Chemistry Education through Practitioner Perspectives. *Int. J. Sci. Educ.* **2021**, 43, 1–22.
- (49) Weaver, G. C.; Burgess, W. D.; Childress, A. L.; Slakey, L. *Transforming Institutions: Undergraduate STEM Education for the 21st Century*; Purdue University Press, 2015.
- (50) Kezar, A. Higher Education Change and Social Networks: A Review of Research. *J. Higher Educ.* **2014**, 85 (1), 91–125.
- (51) Cohen, J. A Power Primer. *Quant. Methods Psychol.* **1992**, 112 (1), 155–159.
- (52) Popova, M.; Shi, L.; Harshman, J.; Kraft, A.; Stains, M. Untangling a Complex Relationship: Teaching Beliefs and Instructional Practices of Assistant Chemistry Faculty at Research-Intensive Institutions. *Chem. Educ. Res. Pract.* **2020**, 21 (2), 513–527.
- (53) Broman, K.; Parchmann, I. Students' Application of Chemical Concepts When Solving Chemistry Problems in Different Contexts. *Chem. Educ. Res. Pr.* **2014**, 15 (4), 516–529.
- (54) Parchmann, I.; Gräsel, C.; Baer, A.; Nentwig, P.; Demuth, R.; Ralle, B. Chemie Im Kontext": A Symbiotic Implementation of a Context-based Teaching and Learning Approach. *Int. J. Sci. Educ.* **2006**, 28 (9), 1041–1062.
- (55) Overton, T. Context and Problem-Based Learning. *New Dir. Teach. Phys. Sci.* **2016**, No. 3, 7–12.
- (56) Overton, T. L.; Byers, B.; Seery, M. K. Context- and Problem-Based Learning in Higher Level Chemistry Education. *Innov. Methods of Teach. Learn. Chem. Higher Educ.* **2009**, 45–61.
- (57) Gilbert, J. K. On the Nature of "Context" in Chemical Education. *Int. J. Sci. Educ.* **2006**, 28 (9), 957–976.
- (58) Brown, J. D. Likert Items and Scales of Measurement? *SHIKEN JALT Test. Eval. SIG Newsl.* **2011**, 15, 10–14.
- (59) ACS Webinars. <https://www.acs.org/content/acs/en/acs-webinars.html> (accessed on November 1, 2021).

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Chapter 3: Identifying chemistry students' baseline systems thinking skills when constructing system maps for a topic on climate change

3.1 Introduction to the manuscript in Chapter 3

Students and educators are stakeholders of a ST approach; therefore, both of their perspectives and experiences on ST need to be investigated to best understand how ST approaches might be implemented and used in chemistry education. Research on these areas has been scarce and use without this research can be counterintuitive if educators are not informed of best practices for ST implementation and if students are not obtaining the proposed benefits of ST. Therefore, we decided to create studies that investigated educators' and students' perspectives and experiences to help bridge these gaps in the literature.

In addition to conducting our educators' perspectives study, we designed a ST intervention to help us understand students' experiences with and perspectives of ST activities. We strategically created the ST intervention to investigate multiple research questions for the overarching ST project. These questions were created based on areas of future ST research indicated in the literature which include cognitive learning gains, affective domain (feelings), and equity, diversity, and inclusion.¹ Given the volume of data we collected from this intervention, this chapter only focuses on students' cognitive learning gains from the ST intervention.

In this study, we investigated chemistry students' baseline ST skills during ST activities without being taught ST prior to the ST intervention. We were interested in learning about what ST skills students do and do not demonstrate naturally during ST tasks, to understand aspects of ST that need more emphasis when teaching ST skills to students and when guiding learning activities and other assessments. While other disciplines have investigated students' ST skills,²⁻⁴ these studies were primarily conducted with K-12 students and not within a chemistry context. Therefore, our study focused on assessing eleven ST skills that aligned with five characteristics of ST in chemistry education proposed by Orgill and York (2020).⁵ Emily Duhart, an Honours student in our research group at the time, helped sift through the ST literature to identify potential ST skills that we could analyze based on the design of this study. I am very thankful for both Emily's and Mann's help with this project.

Eighteen undergraduate students participated in the study and the manuscript in this chapter communicates these students' baseline ST skills when engaging in the ST activities during the ST intervention.

The second part of this chapter communicates the findings from eight graduate students who also participated in this study. There are two reasons why we decided not to include the graduate students' ST skills data in the manuscript: (1) We felt that adding additional findings to the manuscript would overwhelm the reader as there are many findings from the undergraduate student data alone, and (2) The small sample size for graduate students limited the ability to draw strong conclusions about the comparisons between the undergraduate and graduate student data. Mann Ali-Nour, an Honours student, analyzed the graduate student data separately by using the same analytical procedure. I provide a brief comparison of the undergraduate and graduate data in Chapter 3.4 and an explanation of why these findings must be interpreted with caution.

Identifying how to analyze the ST skills was the most challenging aspect of this project, as very little is known about how to assess ST skills in chemistry. I now understand and empathize with chemistry educators who have indicated assessment as a barrier to implementing ST in chemistry education. Because assessment methods are lacking for ST in chemistry education, we incorporated several frameworks and models from the educational and chemistry education literature into an assessment tool for certain ST skills. Given the time and effort put into determining how to assess each skill, we provided a detailed description of how each of the skills was assessed in the supporting information and created an adaptable ST rubric for the chemistry community to use as a tool for assessing ST. My hope in providing these resources is to make it easier for other researchers and educators to investigate ST skills, rather than starting from the beginning.

Our work provides a starting point for understanding how to assess ST skills in chemistry education. Despite this work, the assessment of ST skills in chemistry education remains a topic that requires more investigation.

3.2 References for introduction

- (1) 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>.
- (2) 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>.
- (3) 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>.
- (4) Gilbert, L. A.; Gross, D. S.; Kreutz, K. J. Developing Undergraduate Students' Systems Thinking Skills with an InTeGrate Module. *J. Geosci. Educ.* **2019**, 67 (1), 34–49.
<https://doi.org/10.1080/10899995.2018.1529469>.
- (5) 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>.

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Identifying Chemistry Students' Baseline Systems Thinking Skills When Constructing System Maps for a Topic on Climate Change

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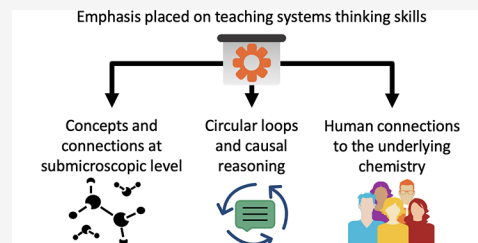
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ABSTRACT: New resources have recently been emerging for educators to implement systems thinking (ST) in chemistry education, including a proposed set of ST skills. While these efforts aim to make ST implementation easier, little is known about how to assess these skills in a chemistry context. In this study, we investigated ST skills employed by students who constructed system maps of a topic related to climate change. Eighteen undergraduate chemistry students from first- to third-year participated in this study. We designed and implemented a ST intervention to capture how students engaged with three ST tasks, performed individually and collaboratively. In our analysis, we focused on 11 ST skills that aligned with five characteristics proposed in a recent study. We found that participants demonstrated most of these ST skills when engaging with the ST tasks, with nuances. Participants' system maps: (1) lacked concepts and connections at the submicroscopic level, (2) included multiple types of connections but few circular loops and causal connections, (3) lacked causal reasoning, although participants did predict how their system maps changed over time, (4) demonstrated the breadth of connections but did not describe human connections to the underlying chemistry of climate change topics. These findings identify aspects of ST where chemistry educators need to place emphasis when teaching ST skills to chemistry students and when guiding learning activities and other assessments. Using our findings, we created an adaptable ST rubric for the chemistry community as a tool for assessing ST skills.

KEYWORDS: Systems Thinking, Qualitative Analysis, First-Year Undergraduate, Second-Year Undergraduate, Upper-Division Undergraduate, Assessment



INTRODUCTION

Consequences from the human transformation of materials in the Anthropocene era have led to emerging global challenges that include global climate change, air pollution, loss of biodiversity, and stratospheric ozone depletion.^{1,2} Since chemistry plays a significant role in the chemical and physical transformations of these materials, citizens and scientists need to consider and explore chemistry's role in addressing these sustainability challenges.^{1,3}

Members of the chemistry and chemistry education communities have recently been promoting a systems approach to highlight the centrality of chemistry in these challenges and guide human action toward sustainability.^{1,4–12} However, a systems thinking (ST) approach is not commonly taught in chemistry courses, leaving graduates unprepared to use the skills needed to tackle these complex global issues. Moreover, educators are inadequately equipped to teach ST in their courses, including the necessary knowledge, instructional resources, and assessment methods.

The proposed benefits of ST from other disciplines propelled interest for implementing ST in chemistry education.^{13–17} The Special Issue of the Journal of Chemical Education: "Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry" included a range of ST resources (e.g.,

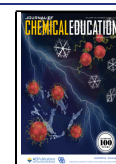
activities, characteristics and skills, demonstrations, laboratory experiments, technology-based learning resources).¹⁸ Additionally, an operational definition of systems-related concepts in chemistry education has been informally proposed by a working group of the IUPAC Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+) Project:^{19,20}

- Systems thinking is the ability to understand and interpret complex problems (ref 21, 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 22, p 39). 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

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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).^{23–27}

Despite all these efforts, only a few studies have focused on assessment related to ST in chemistry education and there are no studies that have investigated how chemistry students naturally engage with ST learning activities (e.g., no prior knowledge on ST).^{9,10,12,22,28,29} While educators' perspectives have indicated limited time to implement and teach ST as barriers of STICE,^{20,30,31} the next steps involve understanding where educators need to place emphasis when teaching ST to students. To know what to emphasize, there is a need to identify what ST skills students are able to readily demonstrate and what skills need more explicit scaffolding in instruction, so that instructional time can be used effectively and efficiently.

The present study is designed to assess ST skills aligned with five characteristics of STICE (Figure 1).²³ These five character-

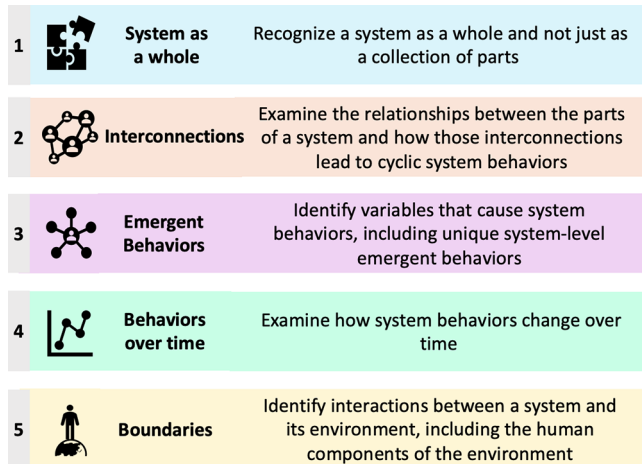


Figure 1. Five characteristics of systems thinking in chemistry education. Adapted with permission from ref 32. Copyright (2020) American Chemical Society.

istics align with the key aspects of STICE stated in the operational definitions provided by the IUPAC STCS 2030+ working group, which is important for maintaining consistency in the implementation and assessment of ST.

Goals and Research Questions

In this study we addressed the following research questions:

- **RQ1:** What ST skills do undergraduate chemistry students use without scaffolding to construct system maps?

- **RQ2:** To what extent do undergraduate chemistry students identify parts of a system (e.g., components, relationships, organization, emergent behaviors, system behaviors, boundaries, and granularity)?

We investigated these research questions to achieve our overarching goal: to identify the baseline skills employed by undergraduate students constructing visual representations of a topic related to climate change, which we refer to throughout as **system maps**.¹² To conduct this study, we designed and implemented a ST intervention to capture how students engage with three ST tasks related to climate change. We chose climate change as a topic to guide the ST tasks 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 participants are given to apply their knowledge to a real-world situation or context.

We aimed to achieve two goals in this study: (1) identify ST skills students do and do not readily demonstrate so that educators can be informed on which skills to explicitly scaffold in their instruction and (2) inform educators and researchers on how to be purposeful when deciding which ST skills to teach, including what prompts to use to elicit ST skills.

METHODS

Instrument and Procedure for Data Collection

We developed a ST intervention that could capture ST skills as chemistry students demonstrated them (Figure 2). This intervention included (1) a pretest (cognitive and affective instruments and a ST question), (2) three ST tasks, and (3) a post-test (the same cognitive and affective instruments and a demographic survey), all completed in one virtual session. We analyzed all instruments for content validity through experts ($N = 2$). Data from the cognitive and affective instruments are not presented in this manuscript but details of these instruments are provided in the [Supporting Information S1.1](#).

This study focused on the three tasks designed to elicit ST skills, individually and collaboratively. To start, participants connected to a virtual session via a zoom link and signed an electronic consent form. The first author (AS) introduced the study and explained the process. Participants then completed a pretest followed by three ST visualization tasks, each of which took approximately 25 min to complete. Throughout the intervention, AS prompted participants to answer questions on a Google Form (details in the [Supporting Information S3](#)).

In the first task, participants individually created a system map on an online collaborative whiteboard platform called Miro. During this task, participants chose one of five topics on climate change, listed concepts related to their topic, and considered chemistry concepts at different levels of granularity on the Google Form. Next, participants created a system map on their topic to show the connections between the concepts they listed.

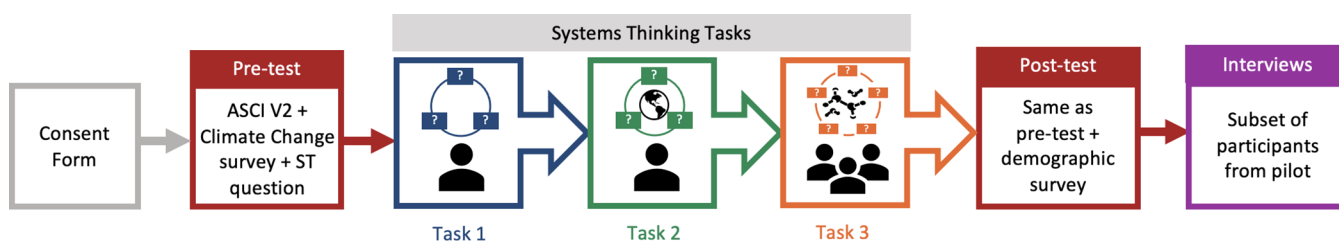


Figure 2. Design of the systems thinking intervention used in this study.

During task one, participants also provided responses to questions that asked them to describe and explain how their system map would change when removing a concept.

Within the second task, participants engaged with an online interactive visualization tool to expand their system map—called the Design Our Climate (DOC) simulation. The DOC simulation is designed to teach citizens about the combination of mitigation strategies that have the greatest potential to reduce greenhouse gas emissions at the global level.³³ Participants first explored the simulation on their own for 5 min and wrote down any relevant information for their system. Next, they watched a short video explaining how to navigate the simulation. Participants then continued to explore the simulation and were prompted to expand their system map based on relevant information they took away from the simulation.

During the third task, AS placed participants in groups of two to three. Participants shared and explained their individual system maps with each other and combined them to form a new system map. Participants completed several questions individually and as a group related to making comparisons between their group and individual system maps.

After completing these tasks, participants completed the post-test instruments and were invited to participate in follow-up interviews to help us gain a better understanding of how students interacted with each task in the intervention. This article will not focus on the findings from these interviews.

Context and Participants

This study was conducted with undergraduate students at the University of Ottawa and received ethics approval through the institution's Office of Research Ethics and Integrity (#H03-20-5585). Participants were recruited via course online platforms from any undergraduate chemistry course (taught in English only) in the Fall 2020 semester. Due to the pandemic, data collection for this study took place entirely through online platforms (i.e., Zoom, Miro, Google Forms).

Eighteen students ranging from first- to fourth-year at the University of Ottawa participated in this study, who had all taken or were taking at least one university chemistry course. All participants provided informed consent.

Theoretical Framework

This research is guided by two overarching theoretical frameworks: (1) modern information processing theory (IPT) and (2) concept map theory.

IPT focuses on how people encode information that is learned and (1) relate encoded information to knowledge in their memory, (2) store new knowledge in their memory, (3) and retrieve the information as needed (Figure 3).³⁴ Advances have

been made to IPT to incorporate learners' characteristics (e.g., decisions, self-regulation, culture, and affect) and the learning environment into the theory, now formally called modern IPT.^{35,36}

Researchers predict that when engaging in ST, each learner will activate a diverse range of prior knowledge from their memory beyond just chemistry knowledge.⁹ Therefore, instructors need to consider strategies for engaging learners' prior knowledge effectively, which can also include learners' experiences, beliefs, and noncontent factors (e.g., attitude, cognitive expectations, motivation, self-concept, self-regulatory strategies, understanding the nature of science).

Modern IPT guided our research by explaining how learners would likely use their prior knowledge in a particular learning environment (e.g., ST intervention) to determine what parts will be embedded in their systems and what parts do not (e.g., components, relationships, organization, granularity, system behaviors). More information about how this theory is embedded into the three ST tasks can be found in the [Supporting Information S1.3](#).

In all tasks, concepts can be retrieved from long-term memory and arranged in working memory to form a mental model of the problem. Mental models are internal cognitive representations that learners use to organize a vast amount of information in an environment into a meaningful system and can be used in generating external representations.³⁴ These external representations can take many forms, including concept maps, which can be used in assessment.^{37–41}

Concept mapping has the potential to measure aspects of how students incorporate facts and concepts into a pre-existing framework of knowledge.⁴² In concept mapping, a student makes connections between a series of concepts related to a particular topic (referred to as concept-links and cross-links) using arrow lines with a statement (propositions/linking words) written above the line describing how the concepts are related.³⁸ The result of this process is a two-dimensional diagram representing their knowledge framework.³⁸

In the study, we used a modification of a well-known concept map scoring method (structural) to assess participants' system maps.³⁸ Since participants were not specifically asked to construct a concept map, we use the term system map throughout this manuscript to best describe the visual representations constructed by the participants. We determined the number of concepts and connections along with their organization in a system map. Concepts, connections, and explanations were not evaluated for correctness as we were not interested in evaluating their knowledge on the subject. A detailed scoring method for participants' system maps used in this study can be found in the [Supporting Information S1.8](#).

Analytical Framework

The scoring method for concept maps was only useful for assessing skills related to concepts, connections, and organization of system maps. Skills related to behaviors, the breadth of connections (e.g., human, environmental, societal), and the types and explanations of connections in system maps needed additional methods of assessment. Because assessment methods are lacking for STICE, we incorporated several frameworks and models into an assessment tool for certain ST skills. The details of each framework are explained in the sections below.

Network Motifs. We used an adapted network motifs framework to understand what types of connections participants made in their system maps. The network motifs in this

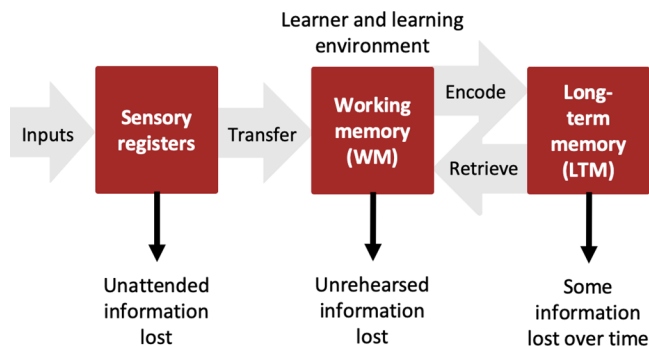


Figure 3. Model of modern information processing theory.

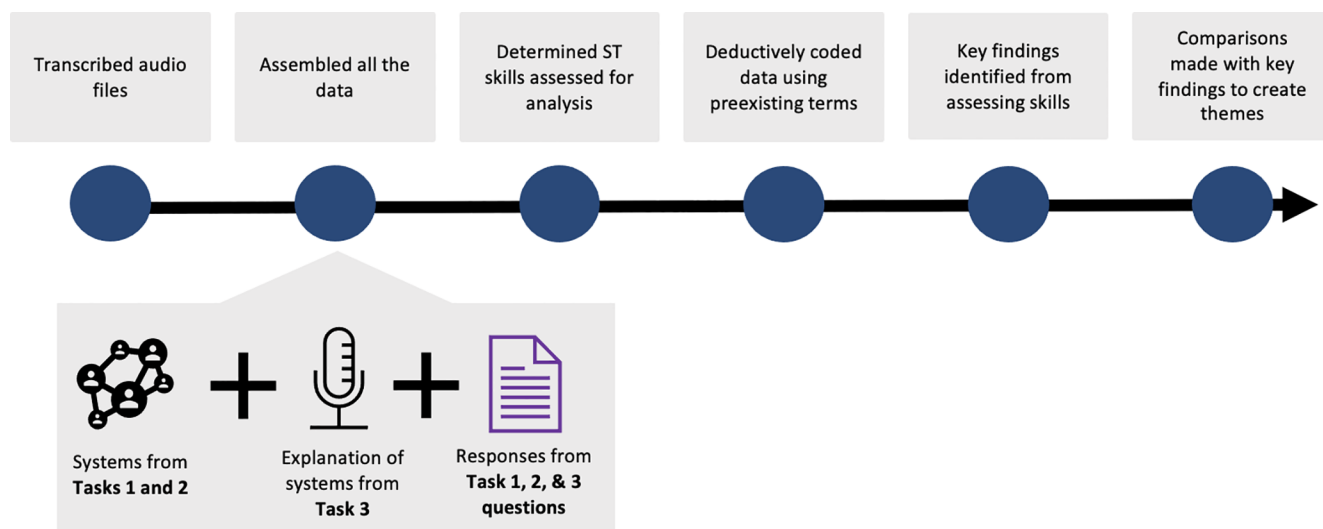


Figure 4. Overview of qualitative analysis procedure for ST study.

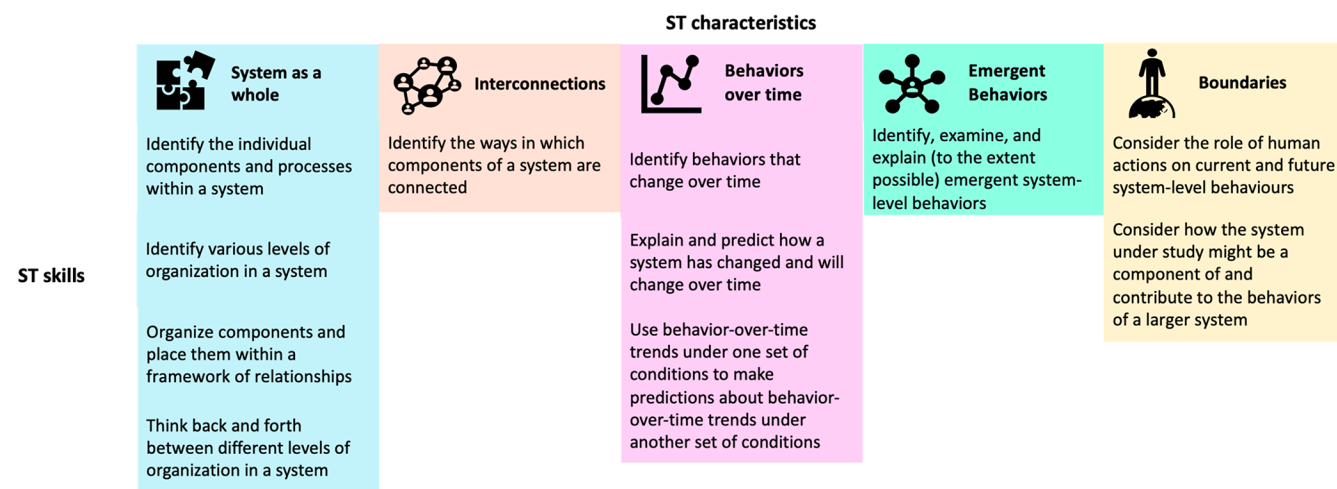


Figure 5. Eleven ST skills chosen for assessment with alignment to five characteristics of STICE.

framework include *multiple inward connections* (two or more arrows pointing toward a concept), *multiple outward connections* (two or more arrows pointing out from one concept), *indirect connection* (extended linear connection), *moderated connections* (an outward connection with the branches closed by an arrow linking back to a concept), *circular loop* (arrows are connected to concepts in a circular pattern and end back at the original concept).⁴³ These connections increase with complexity in the order they appear.

Modes of Reasoning. The reasoning framework commonly used in the chemistry education community helped us understand how students *explain* connections in their system maps.^{44–46} We analyzed students' connections based on modes of reasoning, which include descriptive, relational, linear causal, and multicomponent causal.^{44–47} Descriptive reasoning contains evidence of surface level features or properties to describe the connection between concepts.⁴⁴ Relational reasoning describes the connection between concepts only in a correlative fashion.⁴⁴ Linear causal and multicomponent causal reasoning both describe cause and effect relationships between concepts. Linear causal reasoning only includes single variables that are connected directly to an effect, whereas multicomponent causal includes multiple interconnected factors and variables.⁴⁴ We

were unable to determine the frequency of each mode of reasoning in this study because we did not explicitly ask participants to describe each connection made in their system maps. Instead, this framework served to provide evidence on the different ways students explained connections in their system maps.

Granularity. Granularity is another dimension of the reasoning framework that we used to determine how participants made connections to macroscopic and submicroscopic levels.⁴⁶ Participants' concepts and connections were categorized at seven scalar levels, consistent with macroscopic (e.g., phenomena, application, chemical application and examples, and chemical properties and processes) and submicroscopic (e.g., molecular, atomic, and subatomic) levels of organization. Definitions and examples of each level of granularity are presented in the [Supporting Information S1.8](#).

Environmental and Sustainability Triangular Model. To identify the breadth of connections in participants' system maps, we adapted a triangular model that focuses on three different aspects of environmental and sustainability issues, (1) society, (2) individual, and (3) nature, along with their relationships to each other, with the added context of being chemistry aligned with our study.⁴⁸ The society context is

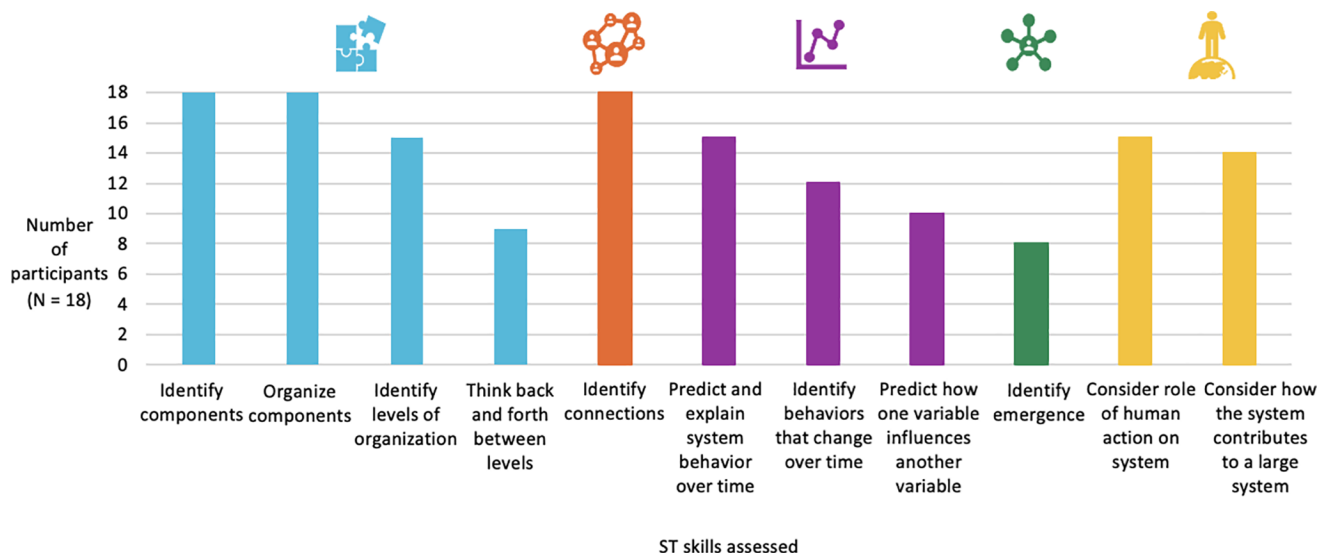


Figure 6. Systems thinking skills participants demonstrated when assessing the skills based on how they are worded from the literature.

related to student' conceptions, norms and values about the social, economic, and political organizations and functions.⁴⁸ The individual context focuses on students' conceptions related to human beings confronted with environmental issues related to climate change.⁴⁸ The nature context focuses on students' conceptions of the phenomenon of climate change.⁴⁸ This model was chosen to identify the connections participants made to different contexts and topics. Definitions of the interrelated contexts are described in the [Supporting Information S1.4](#).

We used these frameworks and models because they aligned with the intended outcomes of the ST skills we chose to assess.

Data Analysis

We analyzed the data using well-established methods in qualitative analysis ([Figure 4](#)).^{49,50}

Qualitative analysis first began by transcribing the audio files and assembling all the data in Microsoft Excel (i.e., transcribed audio scripts, responses from Google Forms, and system maps on the Miro board) to ensure we did not miss any information on how participants demonstrated ST skills (see [Supporting Information S1.6](#) for an example and explanation of the process). Next, we determined the ST skills from the literature to ensure we considered all aspects of ST for assessment. Our search for ST skills began by examining existing literature published on ST skills, characteristics, learning outcomes, or competencies across disciplines such as engineering, chemistry, biology, geoscience, earth science, business, geography, public health, and systems dynamics. We aligned the skills from these disciplines to the 15 skills for STICE proposed by York and Orgill.²³ To capture other relevant aspects from our literature search, we made slight modifications to the 15 skills, creating a total of 20 skills. Our modifications along with critiques of each skill from ST literature are provided in the [Supporting Information S1.7](#). Based on the data, we chose 11 ST skills for assessment that aligned with the five characteristics of STICE ([Figure 5](#)). ST skills not used in analysis along with reasons to exclude these skills can be found in [Table S3](#) in the Supporting Information. We assessed the 11 skills as they are articulated in science education research literature. We coded data aligned with each skill deductively using preexisting terms or frameworks from the literature (e.g., concept mapping, network motifs, reasoning framework, triangular model of aspects of environmental and sustainability

issues).^{38,43,44,48,51} Codebooks for assessing these skills along with related details can be found in the [Supporting Information S1.8](#).

After coding the data for each of the 11 skills, we created graphs and visualizations to determine the key findings. Next, we sorted the key findings and organized into categories while critically debating the presence/absence of codes.⁵² Then, we synthesized the categories similar in nature and derived themes based on the research questions. Writing memos helped communicate the coding process and emerging patterns, categories, and themes in the data among the researchers.⁵³ The record of memos helped ensure confirmability and dependability of the analysis.⁵⁴ We addressed the validity of the findings using well-established methods such as content validation, triangulation, disconfirming evidence, and peer debriefing, justified in the [Supporting Information S1.5](#).^{55,56} In the following sections, we describe the main findings, starting with the key themes that we discovered from our analysis for both research questions.

RESULTS AND DISCUSSION

RQ1: What ST Skills Do Undergraduate Chemistry Students Use without Scaffolding to Construct System Maps?

Most participants demonstrated the 11 ST skills when engaging with the ST tasks ([Figure 6](#)).

The first ST characteristic, **system as a whole** (blue, [Figure 6](#)), assessed four ST skills in which all 18 participants demonstrated the ability to identify components of their system (e.g., concepts in a concept map) and organize the components within a framework of relationships.

Of the participants, 15 also identified levels of organization in their system while only nine demonstrated the ability to think back and forth between these levels (i.e., macroscopic and submicroscopic). Going back and forth between the macroscopic and submicroscopic levels is an important feature of learning in chemistry; however, learners typically struggle with switching back and forth between these levels of representation, which is emphasized in our findings.^{57–61}

We assessed only one skill for the second ST characteristic: **interconnections** (orange, [Figure 6](#)); all participants demonstrated this skill (i.e., identifying connections).

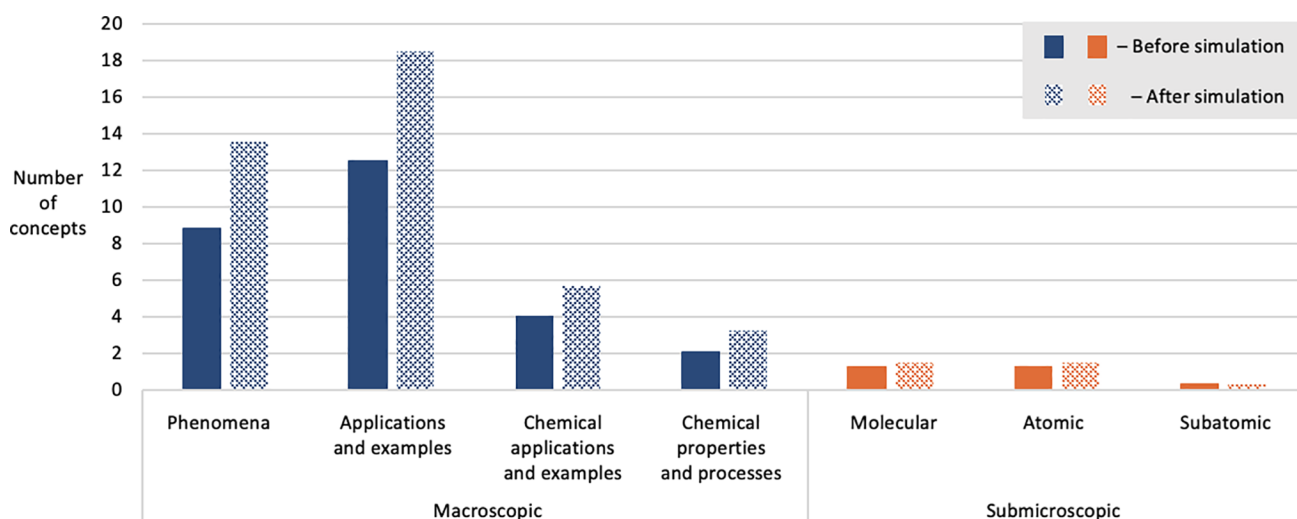


Figure 7. Seven levels of granularity associated with macroscopic and submicroscopic levels used to identify concepts present within students' system maps.

Participants varied in terms of their ability to demonstrate three ST skills related to the third ST characteristic: **behaviors over time** (purple, Figure 6). Behavior over time skills require learners to understand the nonlinearity of a system where multiple variables can influence system behaviors.²³ However, in chemistry curricula, instructors commonly teach single reactions or multiple reactions in linear sequences. Therefore, students may find systems that involve multiple nonlinear behaviors quite challenging.⁶² Our results suggest that students may not have much prior experience dealing with complex dynamic systems in chemistry courses because skills related to behaviors over time were demonstrated less by participants.

The fourth ST characteristic, **emergent behaviors** (green, Figure 6), assessed one skill (i.e., identifying emergence) and only eight participants demonstrated this skill. To identify emergence, one must distinguish a property or behavior that will result from considering interactions between parts of a system.¹ We assumed participants had no prior knowledge about ST and prompted participants by asking them to "identify any similarities and differences between each system map" in the group task. The following quote represents an example of a participant identifying an emergent property (i.e., transporting goods efficiently and being conscious of the environment) when comparing two individual system maps with topics on transportation and land use and agriculture:

"In terms of the transportation subject, had very similar points. [Participant 8] had more to do with researching new ways while mine was more about implementing existing ways that are more efficient. We were able to relate agriculture and land use to our topic through the transport of goods efficiently and being conscious of the environment."

In all cases, participants who identified emergence observed a property at the macroscopic level opposed to the submicroscopic level. Chemistry involves many chemical processes that lead to phenomena observed at the macroscopic level but take place at a molecular scale, requiring learners to understand these invisible processes and think back and forth between these levels of representation.⁶² While our goal was to only identify if students could think about emergence, future research will need to explore students' ability to consider interactions between chemical substances at the molecular level.

Lastly, at least 14 participants demonstrated two skills related to the fifth ST characteristic: **boundaries** (yellow, Figure 6) (i.e., (1) consider the role of human action on the system and (2) consider how the system contributed to a larger system). The first skill was assessed by looking for any connection a participant included that described how human action influences their system map. For example, one participant indicated an action humans can implement to stop climate change: "The most impactful choice we can do to stop climate change is to drive less and carpool more often." For the second skill, we looked for connections participants made to climate change because each of the topics participants chose at the start of the ST intervention was embedded with climate change (a larger system).

Skills related to **boundaries** are unique as they can emphasize the effects of human actions and policies on chemical and global systems, but have not been an essential focus in several lists of ST skills.^{63,64} From a chemistry perspective, acknowledging the implications of decisions in the chemistry laboratory and actions on different systems (e.g., political, social, economic, and environmental) at local, national, and international levels is critical for effectively addressing global challenges such as climate change.⁶³

These findings contribute to answering our first research question by identifying the skills that undergraduate chemistry students naturally use when constructing system maps without explicit scaffolding of STICE. However, when completing our analysis, we realized certain ST skills are composed of multiple aspects and participants demonstrate some of these aspects less frequently or not at all. For example, the skill for **interconnections** looks at students' ability to make connections between components in their system. However, we need to look deeper at the types of connections students make in their system map (e.g., ST aspects) because literature has suggested it is important to identify cyclic behaviors within a system.^{15,23,65–67}

Future work will need to explore these aspects because we do not have any evidence on students' ability to demonstrate these ST aspects. Aspects of ST are initially missed in assessment because some of the skills are broad and can be zoomed in, to achieve finer granularity.^{46,47} Therefore, we looked at the extent to which participants could demonstrate aspects of ST skills so we can understand what students can demonstrate naturally and

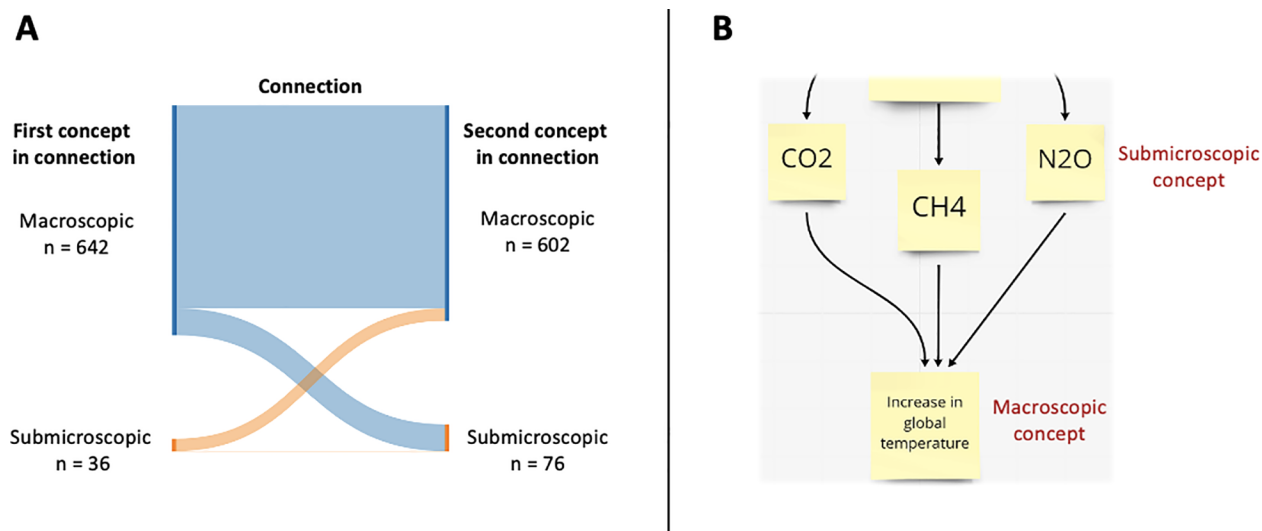


Figure 8. (A) A Sankey diagram indicating the number of connections made between the macroscopic and submicroscopic levels ($N = 678$). The left side of the Sankey diagram indicates the first concept in a connection and the right side is the second concept that it is connected (figure produced using SankeyMATIC). (B) A section of a participants' (P6) system map making several connections from the submicroscopic level to the macroscopic level, e.g., connection made from N₂O (first concept: submicroscopic) to global temperature (second concept: macroscopic).

where emphasis needs to be placed when teaching ST skills to students.

RQ2: To What Extent Do Undergraduate Chemistry Students Identify Parts of a System (e.g., Components, Relationships, Organization, Emergent Behaviors, System Behaviors, Boundaries, and Granularity)?

System Maps Had Substantially More Concepts and Connections at Macroscopic Levels of Granularity than Submicroscopic Levels. Participants' system maps lacked concepts and connections at the submicroscopic level. This finding was uncovered when looking at the extent of participants' ability to identify levels of organization (i.e., macroscopic and submicroscopic) in their system map and connections between them (Figure 7). We looked at the concepts before and after engaging in the DOC simulation because this tool allowed for students to explore primarily macroscopic chemistry connections relating each topic to climate change. Participants' system maps predominately featured concepts of granularity at the macroscopic level (92% of the 531 concepts), which included chemical applications and examples and chemical properties and process. System maps lacked concepts at the molecular, atomic, and subatomic levels. Moreover, the average of the subatomic concepts in participants' system maps after engaging in the simulation increased only slightly or not at all. Given that more emphasis was placed on macroscopic concepts in the simulation, the findings were not surprising. Depending on the intended learning outcomes of a ST task (e.g., include concepts and connections at the submicroscopic level), the nature and purpose of complementary resources used in ST activities needs to be addressed to ensure the resource helps students achieve the intended learning outcomes.

We found limited connections between the macroscopic and submicroscopic levels (Figure 8A). There were only 36 instances where participants' system maps included connections starting with a submicroscopic concept to a macroscopic concept as shown by the example in Figure 8B.

There is evidence to suggest that students struggle to make connections to the submicroscopic level and our findings

emphasize the need to explicitly prompt students to consider concepts and connections at the submicroscopic level.⁵⁸

System Maps Had Multiple Types of Connections but Few Circular Loops and Causal Connections. In their system maps, participants created connections but few circular loops (Figure 9), which has also been found in related

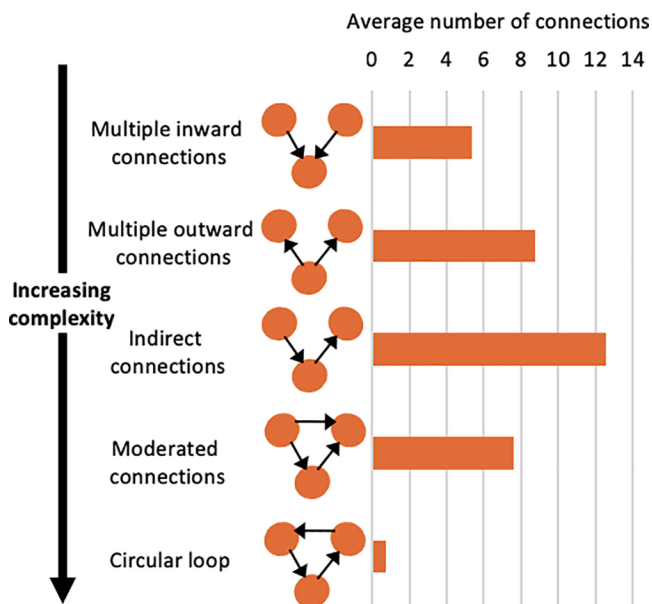


Figure 9. Average number of connections for each type of connection in participants' system maps.

research.⁴³ We found that participants might be more familiar with the more common linear thinking represented by the indirect connections opposed to closed-loop thinking represented by circular connections. Linear thinking involves considering how one variable influences another variable, whereas closed-loop thinking also considers how a subsequent change in the second variable will then influence the first variable.²³ The design of learning activities and associated

prompts can provide good opportunities for students to deal with complexity and advance students' understanding of closed-loop thinking.⁶²

One aspect where our analysis and results differed from other studies was in the way we interpreted causal relationships. Other literature sources have assumed that each arrow in a system map represents a causal link;^{43,68–70} however, our evidence suggests not all connections in a system are causal. Figure 10 represents an example of a circular loop present in a participant's system map.

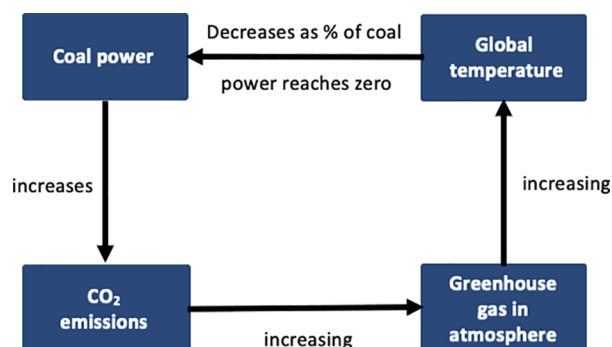


Figure 10. An example of a circular loop from a participant's system map.

While some of the linking words such as “increasing” or “decreasing” could represent a causal connection, we do not have enough evidence to make this claim by only looking at arrows and linking words in a concept map; additional reasoning from the participant would be needed. We analyzed participants' explanations using the modes of reasoning framework with only explicitly available evidence (Figure 11).⁴⁴

Participants reasoned in three ways, (1) descriptive, (2) relational, and (3) linear causal, which provided evidence that not all connections are inherently causal. Overall, relational and descriptive reasoning were the most common among participants' explanations and multicomponent causal reasoning was not present in any connections. Learners tend to describe simple, linear cause and effect terms when behaviors and properties result from a single cause instead of being influenced by multiple causes.^{23,71–73} Most systems are nonlinear and have multiple causes; therefore, students need to learn to use multicomponent causal reasoning to be able to address associated issues and solve complex problems.²³ Participants could have demonstrated multicomponent causal reasoning during a ST task; however, students were not explicitly

prompted to explain each connection in their system map. We only have evidence on how students naturally reasoned about phenomena. We realize the quality of student reasoning is important for assessment and describe it as one of the limitations to our study below. Overall, our findings suggest that educators need to scaffold instruction for creating circular loops and prompt students to use causal reasoning when making connections in system maps. Furthermore, we need other methods of assessment for determining causal connections in systems, such as a reasoning framework.

Participants Could Predict How Their System Maps Changed over Time but Did Not Use Multicomponent Causal Reasoning. Further analysis showed that most participants could predict how their system maps changed over time. However, when explaining how their system map would change, participants did not consider how influencing one concept would impact multiple concepts through cause-and-effect relationships (i.e., multicomponent causal reasoning). At most, participants explained a single chain of causal relationships between two or more concepts in their system map (i.e., linear causal reasoning). Examples of student responses can be found in Table S13 and Table S14 of SI.

We analyzed participants' responses to the following two questions, (1) How does removing the second idea/concept impact the rest of your system? and (2) Why does removing the second idea/concept impact the rest of your system? Participants responded in three ways: (1) no prediction, (2) predicting their system map would partially change, and (3) predicting their system map would holistically change. Participants also explained how their system map would change using the same three types of reasoning (i.e., descriptive, relational, and linear causal) as previously described. The Sankey diagram (Figure 12) shows how each participant predicted and explained how their system maps changed over time, aligned with our main finding. For example, one participant (P12) predicted that their system map would change holistically when removing a concept (in this example, food) from their system map and used a descriptive mode of reasoning in their explanation (Figure 13).

Multicomponent causal reasoning may be considered an important aspect for determining how system behaviors change over time because systems are complex and involve many interconnections. When altering a component of the system map, all pathways connected to this component need to be considered to determine the impact of change. Placing emphasis on teaching multicomponent causal reasoning could help students understand the complexity of systems and factors involved to address complex chemistry problems.

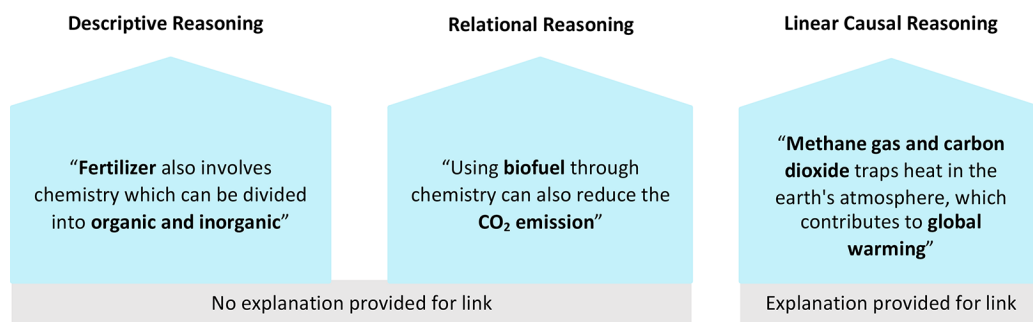


Figure 11. Examples of descriptive, relational, and linear causal reasoning of connections provided by participants; no examples of multicomponent causal reasoning were identified. Bolded words represent concepts in each connection.

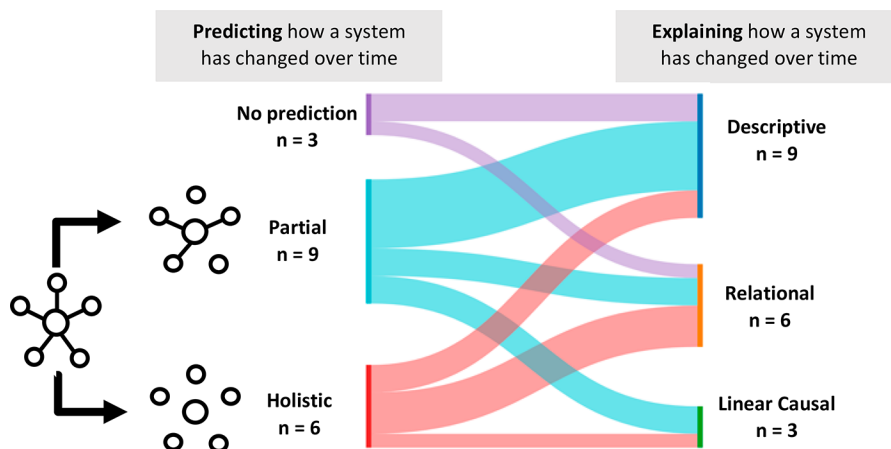


Figure 12. Ways participants predicted and explained how their systems changed over time; no examples of multicomponent causal reasoning were identified.

Predict - Holistic
 “It would completely dismantle the connections between everything because food is central to agriculture”

Explain - Descriptive
 “Humans grow crops for their consumption along with animals that they grow”

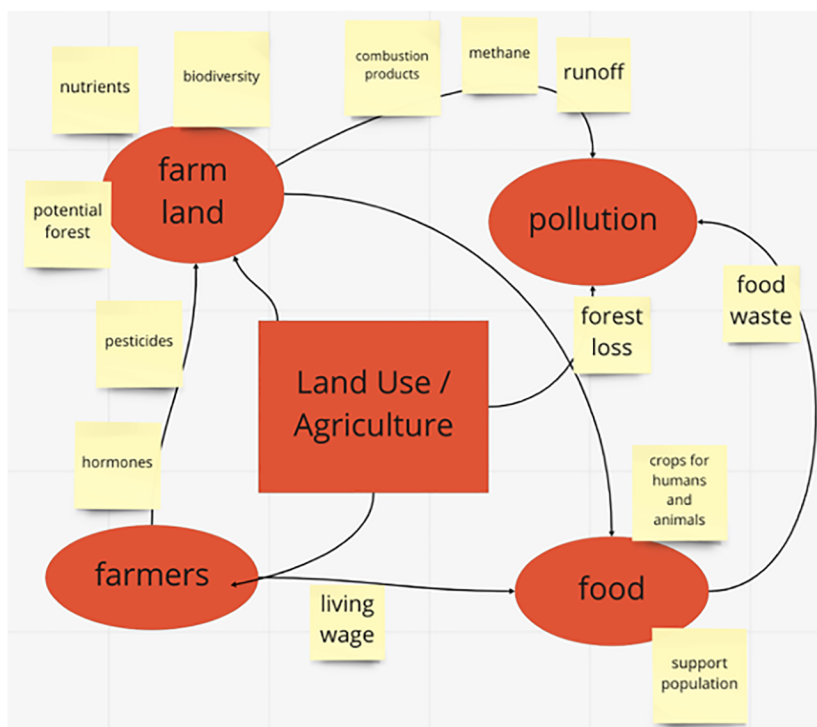


Figure 13. Example of a participants' (P12) system map including their prediction and explanation of how removing a concept would impact the rest of their system map. Food was the concept that this participant removed from their system.

System Maps Had a Breadth of Connections but Did Not Include Human Connections to the Underlying Chemistry. Participants were able to demonstrate the breadth of connections by making links to other disciplines, topics, and contexts but did not make connections that involved human impact on chemistry or how chemistry impacts humans. Fourteen of the 18 participants made at least one connection to a different discipline and/or subdiscipline (e.g., engineering, politics, ecology, biochemistry, mathematics) and/or another DOC simulation topic (e.g., transportation, electricity, land use and agriculture, buildings, materials). Moreover, participants made connections to different contexts particularly those related to the society and nature contexts of the triangular model (Figure 14).⁴⁸ These findings are promising because the breadth of connections that participants demonstrated can lead to the demonstration of other ST skills (e.g., the identification of

boundaries) when explicitly teaching students ST terminology and prompting students with specific questions.

Surprisingly, participants did not include any connections between the individual context and chemistry, indicating they did not consider human impact on chemistry and vice versa. Efforts have been made to bridge human impact and chemistry through the redesign of the postsecondary chemistry curriculum.¹¹ However, our findings suggest there needs to be more widespread institutional efforts to educate students on how chemistry impacts or is impacted by the human context. Several researchers have highlighted the importance of humanizing chemistry education by incorporating considerations of the impact of human activity, benefit-cost-risk analyses, and socio-scientific approaches.^{62,74–77} These efforts highlight the need to connect chemistry to student experience and serve as a good reminder for educators to connect chemistry to the lives of

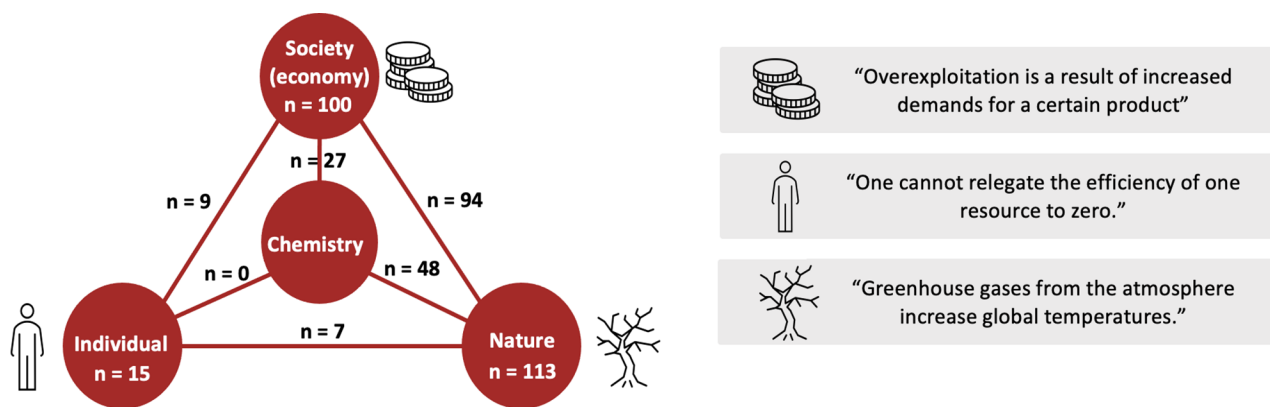


Figure 14. A triangular model of the aspects of environmental and sustainability issues adapted to include chemistry as a related context. Examples of participants' connections to the society, individual, and nature contexts are shown on the right side of the figure.

Table 1. ST Rubric as a Tool for Assessing ST Learning Outcomes Aligned with Five Characteristics of STICE⁴⁴

Systems Thinking Learning Outcomes	Satisfactory	Exceptional
Identify concepts of a system based on a particular topic and create a combination of linear, closed loop, and cyclic connections between concepts, organized in an interconnected fashion. (Examples of each level provided in SI.)	Includes concepts and a combination of linear and closed loop connections with some branching present (some interconnections in system map).	Includes concepts and a combination of linear, closed loop, and cyclic connections with lots of branching (many interconnections in system map).
Include concepts in a system at multiple scalar levels (e.g., macroscopic and submicroscopic) and think back and forth between these levels when making connections between concepts.	Includes concepts at multiple scales (e.g., macroscopic, and submicroscopic) but makes connections between sublevels of one level of granularity (e.g., global, application, chemical property) OR makes connections between these levels primarily in one direction (e.g., macroscopic concept → submicroscopic concept).	Includes concepts at multiple scales (e.g., macroscopic, and submicroscopic) and makes many connections back and forth between these levels (e.g., submicroscopic concept → macroscopic concept and vice versa).
Predict and explain how a system will change over time when removing a concept in the system.	Based on a system that can be affected with change, student predicts their system will partially change (e.g., only some concepts will be affected when removing a concept).	Based on a system that can be affected with change, student predicts their system will holistically change (e.g., when removing a concept, this affects all concepts in the system).
Note: There may be instances where systems may not change (e.g., reaction rate if the reactant is not involved in the rate-determining step). Change criteria in rubric accordingly.	Explains how the system will change using linear causal reasoning. (Examples provided in the SI Table S20.)	Explains how the system will change using multicomponent causal reasoning. (Examples provided in the SI Table S20.)
List similarities between systems then identify a property or behavior that emerges when considering multiple systems together.	Identifies similarities between systems but does not identify a behavior or property that emerges when considering the systems together.	Considers similarities between systems and identifies a behavior or property when considering the systems together.
Create connections to other contexts (i.e., human, societal, and environmental) and other disciplines, and consider chemistry's connection to these contexts and disciplines.	Includes limited connections to other contexts and/or disciplines. Includes limited chemistry connections to these other contexts and/or disciplines.	Includes many connections to other contexts and/or disciplines. Includes many chemistry connections to these other contexts and/or disciplines.
Correctness of connections in system and explanations for ST skills.	Some connections and explanations are supported by appropriate scientific evidence and theories.	All connections and explanations are supported by appropriate scientific evidence and theories.

⁴⁴Note: Systems thinking terminology has been simplified in this rubric to become more user-friendly for educators. The translations of systems thinking terminology used in the paper are as follows: "Scalar levels" refers to levels of organization; "Linear connection" refers to indirect connection from Figure 9; "Closed loop" refers to moderated connections.

students and the public to help prepare learners as chemically literate citizens and responsible scientists.^{75,76}

A Tool for Assessing Five Characteristics of STICE

Here, we provide a ST rubric developed from our analysis and findings (Table 1). Research suggests students need explicit instruction and scaffolding to help them develop ST skills and achieve intended ST learning outcomes.^{23,78,79} This rubric addresses this challenge by (1) prompting educators to identify how they plan to assess learning outcomes within ST learning activities, and (2) informing students of how they will be assessed with respect to the learning outcomes within a ST learning activity.

Based on the intended learning outcomes of a specific ST task, the rubric can be modified to elicit these learning outcomes and the levels at which they may be achieved. First, educators should

identify the learning outcomes of a ST task. The learning outcomes should elicit characteristics of STICE to be consistent with a ST approach.³² Then, using our findings and other literature sources, educators should identify the levels (if any) of how the learning outcome can be achieved by students (e.g., only presence of linear connections compared to presence of linear and cyclic connections). Future research will be needed to explore how to assign quantitative scores to ST skills based on the weight of importance and difficulty of ST skills by the chemistry education community.

Not all ST skills from the literature are elicited in this rubric; the ST skills that are assessed with this tool were chosen based on alignment with the learning tasks in our ST intervention. This rubric provides a way to assess ST tasks that encompass multiple forms of assessment tasks including concept maps, and written

and verbal responses, which has not previously been shown in the literature (Table 1).

■ IMPLICATIONS FOR TEACHING AND RESEARCH

If we expect students to demonstrate specific aspects of ST skills, then as educators we need to be purposeful and explicit about what ST skills are taught and what prompts and scaffolds are used to elicit these skills so that chemistry students are equipped for success.

Explicit prompts are needed for students to consider concepts and connections at the submicroscopic level. There are several pedagogical approaches for helping students to connect the particulate and macroscopic levels in a ST context, each with opportunities for students to practice and receive feedback.⁶² For example, instructors can: (1) be more explicit in explaining transitions, (2) design tasks for student to visualize, (3) explore and make connections between levels of complexity, and (4) use different “what-if” scenarios involving perturbations of a system.⁶²

Educators should scaffold instruction for creating circular loops and prompt students to use causal reasoning when making connections in system maps. Engaging in closed loop thinking can help students to understand circular behaviors in a system. Teaching students how to engage in this type of thinking and providing opportunities to practice with complex problems regularly will complement the more typical linear thinking approach. Chain reaction mechanisms provide one example of a tool to illustrate a closed feedback loop in a chemistry course.⁶² The cyclic nature of these mechanisms may not be easy for students to understand; however, the mechanism at hand can provide opportunities to discuss circular loops from a chemistry context.⁶² Considering many educators' current lack of knowledge on STICE,²⁰ ST experts and researchers should provide more examples of closed-loop thinking for different areas of chemistry (e.g., general, organic, and physical chemistry) that educators can use in their courses.

When teaching students about closed loop thinking, causality should be emphasized as a key aspect. To elicit causal reasoning, students can be first asked to look for variables that cause behaviors in their system map then to use causal reasoning to explain the connections of these variables in their system maps. This implication emphasizes the reasoning framework as an effective tool for determining causal connections in system maps when explicitly asking students to explain connections. Future research on assessing ST skills will need to consider other methods of assessment for determining causal connections in system maps, such as a reasoning framework.

Causal reasoning was lacking in participants' explanations of how their system maps would change over time. When considering perturbations to a system, visualizations, modeling, and discussions (qualitative and quantitative) can be incorporated into instruction.⁶² These approaches can provide opportunities for instructors to demonstrate multicomponent causal reasoning and allow students to gain skills explaining causal relationships.

In addition to educators emphasizing the components and interrelated connections in chemistry content,⁸⁰ human impact is a fourth component that needs to be integrated more into pedagogy.⁷⁵ Here, we emphasize the need for educators to be purposeful about what prompts to use when expecting students to demonstrate certain ST skills in a ST learning activity. The ST learning outcomes in the ST rubric can serve as a guideline for creating prompts that can help students elicit intended ST skills.

■ CONCLUSIONS

Educators' perspectives on a STICE approach have shown that *time to teach and learn ST and lack of assessment tools* are prominent barriers to implementing a ST approach.^{20,30,31} Our study investigated the ST skills chemistry students do and do not naturally demonstrate during ST tasks, to understand where to place emphasis on teaching ST skills in a chemistry course. A tool for assessing aspects of ST skills was produced from insights on our analysis and findings. We used five characteristics of STICE as a framework to identify what a systems thinker in chemistry education should demonstrate during an activity that follows a ST approach. Most participants were able to demonstrate the 11 ST skills that were assessed. However, when assessing ST skills based on how they are articulated in the literature, aspects of ST were missed. Therefore, we further investigated the extent that participants demonstrated these ST aspects.

Participants' system maps lacked concepts and connections at submicroscopic levels of granularity (e.g., molecular, atomic, subatomic). Educators' time for teaching ST can be placed on emphasizing concepts at the submicroscopic level and making connections from concepts at the macroscopic level to the molecular level and vice versa.

Participants' system maps included multiple types of connections but limited circular loops and causal connections. Current methods for determining causal links in student system maps are insufficient (i.e., arrows between concepts). Therefore, we used a reasoning framework to identify ways participants described connections in their system maps and found they often lacked causal reasoning. Forming circular loops and using causal reasoning are ST aspects that also need more explicit prompting and scaffolding in learning activities by educators.

Lack of causal reasoning was also found in participants' explanations to how their system maps would change over time. Again, this finding emphasizes the need to teach students how to reason about causal relationships, particularly with relationships that involve multicomponent causal reasoning when determining behaviors over time.

Lastly, participants' system maps demonstrated the breadth of connections but did not include connections in their system maps that considered human impact on chemistry. Therefore, educators need to draw more attention toward connections to human dimensions when teaching chemistry concepts to students. Participants' connections to other disciplines, topics, and contexts can also lead to the identification of boundaries when explicitly prompting students with a specific question.

Our results provide a starting point for understanding how to assess ST skills in chemistry education.

■ LIMITATIONS

There are several limitations on what we may conclude given the study design and analysis procedures. First, we could not assess all skills from the literature as we did not include specific prompts in the ST intervention (e.g., What is the purpose of your visual representation? What are the boundaries of your visual representation?). Therefore, future research will be needed to identify chemistry students' abilities to demonstrate these skills (e.g., identify the purpose of the system, examining positive and negative feedback loops within a system, identify and explain the causes of cyclic behaviors within a system, identify multiple variables that influence a given behavior of a system). While this study only focused on identifying whether

participants demonstrated ST skills, we did not assess the quality of concept connections in their system maps or student reasoning, as it was beyond the scope of this study. Additionally, there is a limitation to how we interpreted the direction of arrows between concepts. We analyzed students' connections based on how they were drawn in their system maps and added arrows to these maps based on the sentence structure of students' explanations. It is possible a connection between two concepts could be represented by the opposite direction of an arrow, but we only included arrows based on the data collected. Lastly, due to the limited number of participants in our study, we cannot generalize these findings to other contexts and further studies are needed.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00955>.

More details about the methods, data analysis, and themes as well as the code books (e.g., themes, categories, description of categories, and representative quotes) for this study; The Systems Thinking Intervention is included for more context (PDF) (DOCX)

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Author Contributions

ARS, PGM, and ABF conceived the project and designed the research questions and methods. ARS collected and analyzed the data. All authors discussed the analysis, results, and conclusions. ARS wrote the first draft of the manuscript. ARS, ABF, and PGM edited and revised the manuscript.

Notes

The authors declare no competing financial interest.

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■ REFERENCES

- (1) Whalen, J. M.; Matlin, S. A.; Holme, T. A.; Stewart, J. J.; Mahaffy, P. G. Transforming the Science of Transformation toward Sustainability: The Case of Ammonia and Reactive Nitrogen. *ChemRxiv*, May 30, 2022. DOI: 10.26434/chemrxiv-2022-nw6k6n.
- (2) Waters, C. N.; Zalasiewicz, J.; Summerhayes, C.; Barnosky, A. D.; Poirier, C.; Galuszka, A.; Cearreta, A.; Edgeworth, M.; Ellis, E. C.; Ellis, M.; Jeandel, C.; Leinfelder, R.; McNeill, J. R.; Richter, D.; Steffen, W.; Syvitski, J.; Vidas, D.; Wagerich, M.; Williams, M.; Zhisheng, A.; Grinevald, J.; Odada, E.; Oreskes, N.; Wolfe, A. P. The Anthropocene Is Functionally and Stratigraphically Distinct from the Holocene. *Science* **2016**, 351 (6269), aad2622.
- (3) National Research Council. *Beyond the Molecular Frontier: Challenges for Chemistry and Chemical Engineering*; National Academies Press, 2003. DOI: 10.17226/10633.
- (4) 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.
- (5) 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.
- (6) Chemistry Education Needs a Green Reset. *Nature* **2022**, 604 (598), 598.
- (7) Wissinger, J. E.; Visa, A.; Saha, B. B.; Matlin, S. A.; Mahaffy, P. G.; Kümmerer, K.; Cornell, S. Integrating Sustainability into Learning in Chemistry. *J. Chem. Educ.* **2021**, 98 (4), 1061–1063.
- (8) Aubrecht, K. B.; Bourgeois, M.; Brush, E. J.; MacKellar, J.; Wissinger, J. E. Integrating Green Chemistry in the Curriculum: Building Student Skills in Systems Thinking, Safety, and Sustainability. *J. Chem. Educ.* **2019**, 96 (12), 2872–2880.
- (9) Eaton, A. C.; Delaney, S.; Schultz, M. Situating Sustainable Development within Secondary Chemistry Education via Systems Thinking: A Depth Study Approach. *J. Chem. Educ.* **2019**, 96 (12), 2968–2974.
- (10) Holme, T. Incorporating Elements of Green and Sustainable Chemistry in General Chemistry via Systems Thinking. In *Integrating Green and Sustainable Chemistry Principles into Education*; Elsevier, 2019; pp 31–47.
- (11) 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.
- (12) 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.
- (13) 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.
- (14) 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.
- (15) Frank, M. Engineering Systems Thinking and Systems Thinking. *Syst. Eng.* **2000**, 3 (3), 163–168.
- (16) 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.
- (17) 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.
- (18) 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.
- (19) *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 on April 6, 2022).
- (20) 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**, 99, 2474.

(21) 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.

(22) Talanquer, V. Some Insights into Assessing Chemical Systems Thinking. *J. Chem. Educ.* **2019**, 96, 2918.

(23) 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.

(24) 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.

(25) 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.

(26) 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.

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

(28) Hrin, T. N.; Milenković, D. D.; Segedinac, M. D.; Horvat, S. Systems Thinking in Chemistry Classroom: The Influence of Systemic Synthesis Questions on Its Development and Assessment. *Think. Ski. Creat.* **2017**, 23, 175–187.

(29) Reynders, M.; Pilcher, L. A.; Potgieter, M. Teaching and Assessing Systems Thinking in First-Year Chemistry. *J. Chem. Educ.* **2023**, 100 (3), 1357–1365.

(30) Delaney, S.; Ferguson, J. P.; Schultz, M. Exploring Opportunities to Incorporate Systems Thinking into Secondary and Tertiary Chemistry Education through Practitioner Perspectives. *Int. J. Sci. Educ.* **2021**, 43 (16), 2618–2639.

(31) 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.

(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.

(33) Mahaffy, P. G.; Brian, M.; Melanie, H.; Robert, M.; Ciezki, A.; Tilstra, M.; Elgersma, A.; Lasola, K.; Vanderwekken, L.; Keeler, T.; Schwalfenberg, A.; Darrell, V.; Joseph, Z. *Design Our Climate Simulation*. <https://applets.kcv.s.ca/DesignOurClimate/DesignOurClimateSim.html> (accessed on January 31, 2020).

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

(35) Mayer, R. E. Information Processing. In *APA Educational Psychology Handbook: Theories, Constructs, and Critical Issues*; APA Handbooks in Psychology; American Psychological Association: Washington, DC, 2012; Vol. 1, pp 85–99. DOI: 10.1037/13273-004.

(36) Pazicni, S.; Flynn, A. B. Systems Thinking in Chemistry Education: Theoretical Challenges and Opportunities. *J. Chem. Educ.* **2019**, 96 (12), 2752–2763.

(37) Besterfield-Sacre, M.; Gerchak, J.; Lyons, M. R.; Shuman, L. J.; Wolfe, H. Scoring Concept Maps: An Integrated Rubric for Assessing Engineering Education. *J. Eng. Educ.* **2004**, 93 (2), 105–115.

(38) Novak, J. D.; Gowin, D. B. *Learning How to Learn*; Cambridge University Press: Cambridge [Cambridgeshire]; New York, 1984.

(39) Brandstädter, K.; Harms, U.; Großschädl, J. Assessing System Thinking Through Different Concept-Mapping Practices. *Int. J. Sci. Educ.* **2012**, 34 (14), 2147–2170.

(40) Walker, J. M. T.; King, P. H. Concept Mapping as a Form of Student Assessment and Instruction in the Domain of Bioengineering. *J. Eng. Educ.* **2003**, 92 (2), 167–178.

(41) Francisco, J. S.; Nakhleh, M. B.; Nurrenbern, S. C.; Miller, M. L. Assessing Student Understanding of General Chemistry with Concept Mapping. *J. Chem. Educ.* **2002**, 79 (2), 248.

(42) West, D. C.; Park, J. K.; Pomeroy, J. R.; Sandoval, J. Concept Mapping Assessment in Medical Education: A Comparison of Two Scoring Systems: Concept Mapping Assessment. *Med. Educ.* **2002**, 36 (9), 820–826.

(43) Levy, M. A.; Lubell, M. N.; McRoberts, N. The Structure of Mental Models of Sustainable Agriculture. *Nat. Sustain.* **2018**, 1 (8), 413–420.

(44) Sevan, H.; Talanquer, V. Rethinking Chemistry: A Learning Progression on Chemical Thinking. *Chem. Educ. Res. Pr.* **2014**, 15 (1), 10–23.

(45) Weinrich, M. L.; Talanquer, V. Mapping Students' Modes of Reasoning When Thinking about Chemical Reactions Used to Make a Desired Product. *Chem. Educ. Res. Pract.* **2016**, 17 (2), 394–406.

(46) 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.

(47) 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.

(48) Sternäng, L.; Lundholm, C. Climate Change and Costs: Investigating Students' Reasoning on Nature and Economic Development. *Environ. Educ. Res.* **2012**, 18 (3), 417–436.

(49) 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, 2003.

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

(51) Saldaña, J. First Cycle Coding Methods. In *The Coding Manual for Qualitative Researchers*; SAGE: Los Angeles, 2013; pp 58–186.

(52) Saldaña, J. Second Cycle Coding Methods. In *The Coding Manual for Qualitative Researchers*; SAGE: Los Angeles, 2013; pp 207–245.

(53) Saldaña, J. Writing Analytic Methods. In *The Coding Manual for Qualitative Researchers*; SAGE: Los Angeles, 2013; pp 41–57.

(54) Birks, M.; Chapman, Y.; Francis, K. Memoing in Qualitative Research: Probing Data and Processes. *J. Res. Nurs.* **2008**, 13 (1), 68–75.

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

(56) Creswell, J. W.; Miller, D. L. Determining Validity in Qualitative Inquiry. *Theory Pract.* **2000**, 39 (3), 124–130.

(57) Talanquer, V. Progressions in Reasoning about Structure-Property Relationships. *Chem. Educ. Res. Pract.* **2018**, 19 (4), 998–1009.

(58) 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.

(59) Johnstone, A. H. Teaching of Chemistry - Logical or Psychological? *Chem. Educ. Res. Pr.* **2000**, 1 (1), 9–15.

(60) *Multiple Representations in Chemical Education*; Gilbert, J. K., Treagust, D., Eds.; Models and Modeling in Science Education; Springer Netherlands: Dordrecht, 2009; Vol. 4. DOI: 10.1007/978-1-4020-8872-8.

(61) 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.

(62) Ho, F. M. Turning Challenges into Opportunities for Promoting Systems Thinking through Chemistry Education. *J. Chem. Educ.* **2019**, 96 (12), 2764–2776.

(63) Orgill, M.; York, S.; MacKellar, J. Introduction to Systems Thinking for the Chemistry Education Community. *J. Chem. Educ.* **2019**, 96 (12), 2720–2729.

(64) Calhoun, J. G.; Ramiah, K.; Weist, E. M.; Shortell, S. M. Development of a Core Competency Model for the Master of Public Health Degree. *Am. J. Public Health* **2008**, 98 (9), 1598–1607.

- (65) 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.
- (66) Kali, Y.; Orion, N.; Eylon, B.-S. Effect of Knowledge Integration Activities on Students' Perception of the Earth's Crust as a Cyclic System. *J. Res. Sci. Teach.* **2003**, *40* (6), 545–565.
- (67) Sweeney, L. B.; Sterman, J. D. Bathtub Dynamics: Initial Results of a Systems Thinking Inventory. *Syst. Dyn. Rev.* **2000**, *16* (4), 249–286.
- (68) Plate, R. Assessing Individuals' Understanding of Nonlinear Causal Structures in Complex Systems. *Syst. Dyn. Rev.* **2010**, *26* (1), 19–33.
- (69) Plate, R.; Monroe, M. A Structure for Assessing Systems Thinking. *Creative Learning Exchange* **2014**, 1–12.
- (70) Grotzer, T.; Bell-Basca, B. S.; Donis, K.; Shaw, S. Using Domino and Relational Causality to Analyze Ecosystems: Realizing What Goes Around Comes Around. In *Annual Meeting of the National Association of Research in Science Teaching*; New Orleans, LA, April 28–May 1, 2000.
- (71) Raia, F. Students' Understanding of Complex Dynamic Systems. *J. Geosci. Educ.* **2005**, *53* (3), 297–308.
- (72) Hogan, K. Assessing Students' Systems Reasoning in Ecology. *J. Biol. Educ.* **2000**, *35* (1), 22–28.
- (73) Raia, F. Causality in Complex Dynamic Systems: A Challenge in Earth Systems Science Education. *J. Geosci. Educ.* **2008**, *56* (1), 81–94.
- (74) Mahaffy, P. The Future Shape of Chemistry Education. *Chem. Educ. Res. Pr.* **2004**, *5* (3), 229–245.
- (75) Mahaffy, P. Moving Chemistry Education into 3D: A Tetrahedral Metaphor for Understanding Chemistry. Union Carbide Award for Chemical Education. *J. Chem. Educ.* **2006**, *83* (1), 49.
- (76) Sjöström, J.; Talanquer, V. Humanizing Chemistry Education: From Simple Contextualization to Multifaceted Problematization. *J. Chem. Educ.* **2014**, *91* (8), 1125–1131.
- (77) Cullipher, S.; Sevan, H.; Talanquer, V. Reasoning about Benefits, Costs, and Risks of Chemical Substances: Mapping Different Levels of Sophistication. *Chem. Educ. Res. Pract.* **2015**, *16* (2), 377–392.
- (78) Forrester, J. W. Learning through System Dynamics as Preparation for the 21st Century: Learning through System Dynamics for the 21st Century. *Syst. Dyn. Rev.* **2016**, *32* (3–4), 187–203.
- (79) Hmelo-Silver, C. E.; Azevedo, R. Understanding Complex Systems: Some Core Challenges. *J. Learn. Sci.* **2006**, *15* (1), 53–61.
- (80) Johnstone, A. H. Why Is Science Difficult to Learn? Things Are Seldom What They Seem. *J. Comput. Assist. Learn.* **1991**, *7* (2), 75–83.

3.4 Undergraduate and graduate student comparison of baseline systems thinking skills

3.4.1 Introduction

Understanding and tackling 21st-century challenges, such as those prioritized by the United Nations Sustainable Development Goals requires a systems lens, such as analyzing the problem from a holistic perspective.¹ Systems thinking (ST) is an approach proposed to help address these 21st-century challenges as it focuses on understanding and analyzing complex systems.^{2,3} Therefore, equipping citizens and scientists with the knowledge and skills required to understand and contribute toward these global challenges requires them to engage in complexity. In particular, understanding complex systems requires the construction of a network of concepts and principles that represents dynamic phenomena and their interrelationships.⁴

Previous studies have investigated expert-novice differences in how they think about complex systems.^{4,5} Prior research shows that novices tend to focus on visible structures when grappling with complex systems,⁶⁻⁸ and have challenges comprehending multicomponent phenomena that are invisible, dynamic, and interdependent due to the high demand for their working memory.⁹ Additionally, making connections between different levels of a complex system increases their cognitive load, especially given the complex causality of systems.¹⁰

Novices' understanding of complex systems is also often hindered by prior experiences that favour explanations including single causality.¹¹ For instance, Jacobson (2001) found that undergraduate students, compared to complex system experts, tended to prefer explanations grounded in linear cause-effect relationships.¹² Similarly, other research has shown that students' reasoning about a range of complex system tend to include simple causal explanations.¹⁰ Researchers suggest that learners focus more on the structure of systems rather than the underlying function.

Another possible cognitive barrier for learners in understanding complex systems may be due to the types of processes that are involved in a system.⁵ Direct processes include cause-and-effect relationships that are obvious whereas emergent processes include cause-and-effect relationships that may be less obvious.⁵ Understanding and recognizing emergent processes requires a prior understanding that a system has multiples causal factors at the macroscopic and submicroscopic levels.⁵

Preliminary research in environmental science has reported differences between novice and experts understandings of aquarium ecosystems with respect to their knowledge organization of this complex system.⁴ They found that novices' representations of an aquatic system focused on static components of the system, whereas experts integrated structural, behavioral, and functional elements

of the system.⁴ These researchers completed a follow-up study with an increased sample size to determine if the differences could be generalized to other complex systems. Results of this study showed that system structures (i.e., elements) are easier for novices to comprehend than the systems' functions or behaviours.⁵ However, for the experts, the behaviours and functions of the system were shown based on how they organized their knowledge of the system.⁵ Researchers have emphasized that "understanding the behaviours and functions of a system indicates a more elaborate network of ideas representing key phenomena and their interrelationships".⁵ Implications from this research focus on the design of instruction to support students' learning about complex systems.⁵

Based on this previous research, we were interested in exploring how students with different levels of chemistry experience and expertise would demonstrate ST skills in chemistry education.

3.4.2 Research Questions and Goals

In this analysis, we address the following research questions:

RQ1: What ST skills do undergraduate and graduate chemistry students use without scaffolding to construct system maps

RQ2: To what extent do undergraduate and graduate chemistry students identify parts of a system (e.g., components, relationships, organization, emergent behaviours, system behaviours, boundaries, and granularity)?

We investigated these research questions to achieve our overarching goal: to understand how different levels of experience in chemistry (e.g., graduate versus undergraduate students) might impact the types of ST skills students demonstrate naturally (e.g., without being taught ST and without scaffolding to construct system maps). Therefore, we made comparisons between undergraduate and graduate students' data to achieve this goal and investigate the research questions.

3.4.3 Methods

We used the same instrument and procedure for data collection to capture undergraduate and graduate ST skills as outlined in the manuscript in Chapter 3.3. Eighteen undergraduate students and eight graduate students participated in this study. Graduate student participants were recruited via the departments' CHMGRAD listserv. All participants provided informed consent. Due to technical complications, we were unable to obtain data on graduate system maps before engaging in the Design Our Climate simulation.

We used the same analysis procedure and theoretical and analytical frameworks as described in Chapter 3.3 to investigate the research questions. Mann Ali-Nour, an undergraduate Honour's student,

coded the graduate student data for each of the 11 skills assessed. To establish reliability of the findings, I reviewed the coding for the eight graduate students and then we discussed and made changes to the coding until we reached an agreement. To compare undergraduate and graduate students, the findings from Chapter 3.3 were compiled with the findings of the graduate students' ST skill analysis. No statistical analyses were completed due to the limitation of the small sample size, especially for graduate students. Therefore, the findings described below are only a qualitative explanation of what the data shows us. Since we cannot make any further conclusions beyond these qualitative explanations, future studies will need to focus on increasing the sample size to further investigate the research questions.

3.4.4 Results and Discussion

RQ1: What ST skills do undergraduate and graduate chemistry students use without scaffolding to construct system maps

Both graduate and undergraduate students demonstrated most of the 11 ST skills when engaging with the ST tasks (Figure 14). Given the differences in the number of participants among the two groups, we looked at the percentage of participants within each group who demonstrated each ST skill.

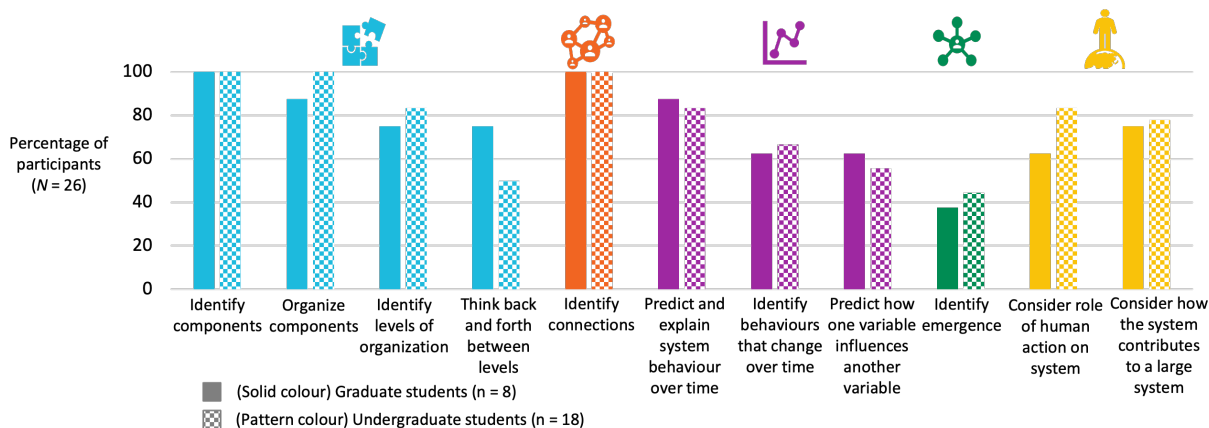


Figure 14. Systems thinking skills graduate students and undergraduate students demonstrated when assessing the skills based on how the skills are worded from the literature. An in-depth description of the assessment protocol for each skill is described in Chapter 8.2 Appendix 2. The solid colour represents the number of skills demonstrated by graduate students, and the patterned colour represents the number of skills demonstrated by undergraduate students.

Among the first four ST skills assessed, that relate to the **system as a whole** characteristic (blue, Figure 14), all 26 students demonstrated the ability to identify components of their topic. Most students organized the components within a framework of relationships (e.g., having at least one concept in the system map connect to at least 3 other concepts), except for one graduate student who created a

prominently linear system map. When assessing students' ability to identify levels of organization (e.g., macroscopic and submicroscopic) in their system map, six graduate students and 15 undergraduate students demonstrated this ST skill. Therefore, some students in both groups only included concepts at the macroscopic level, suggesting that thinking at the molecular level could be a challenge regardless of chemistry experience. The same can be said about students' ability to move back and forth between the macroscopic and submicroscopic levels. Six graduate students and nine undergraduate students demonstrated this ST skill of thinking back and forth between these levels, which has been previously indicated as a challenge in the literature.^{13–16}

All 26 students demonstrated the ability to **identify connections** (orange, Figure 14) of their chosen topic, regardless of the level of complexity of these connections. The types of connections students demonstrated are described in the findings under the second research question.

Both graduate and undergraduate students varied in terms of their ability to demonstrate the ST skills related to the **behaviours over time** characteristic (purple, Figure 14). As suggested in Chapter 3.3, students may not have much prior experience dealing with complex dynamic systems in chemistry courses or may not view the topic of their system map as a complex dynamic system; therefore, they demonstrate these skills less frequently. These data suggest that graduate students might have been taught using a chemistry curriculum similar to the one taught at the University of Ottawa where chemistry concepts are typically taught in linear sequences except for catalysis, taught in upper-year courses. However, we did not collect data on the institutions graduate students attended for their undergraduate studies so we cannot make this conclusion with certainty. Additionally, students may struggle to identify the behaviours of a system over time if they do not have a strong foundation of chemistry knowledge on the topic and with not being prompted to look for that information. Overall, the findings suggest these skills need to be explicitly taught and scaffolded in both undergraduate and graduate chemistry courses if students are expected to demonstrate these skills in ST tasks.

We found a similar trend for students' abilities to **identify emergence** (green, Figure 14)—undergraduate and graduate students demonstrated this skill the least frequently. However, the data must be interpreted with caution, as two of the graduate students did not complete task 3, which was designed to assess emergence. There could be multiple reasons why students demonstrated this skill the least.

First, emergence is an unfamiliar concept in chemistry since it is often not used to describe the observation of a chemistry property or behaviour. However, emergence is a fundamental aspect of chemistry as there are many chemical processes that lead to phenomena observed at the macroscopic

level but occur at the molecular level, requiring a chemist to think back and forth between these levels. Our data and prior literature tell us that students have challenges with thinking back and forth between these levels; therefore, we cannot expect students to identify emergence if they have not mastered these underlying skills. Students need to be first taught to make connections between macroscopic and submicroscopic concepts. After students have opportunities to practice and be assessed on this skill, then educators can add the next layer of complexity in their teaching, identifying emergence.

Secondly, because Task 3 was completed in groups, the group dynamics may have influenced how students identified emergence. We elaborate on this hypothesis in the research presented in Chapter 4. Additionally, follow-up interviews described in Chapter 4 offer some insight into how students answered the question assessing their ability to identify emergence. However, not all participants participated in these interviews, limiting our ability to determine why some students demonstrate the skill and why others did not.

Lastly, at least five graduate students and fourteen undergraduate students demonstrated the two skills related to the ST characteristic: boundaries (yellow, Figure 14) (i.e., (1) consider the role of human action on the system and (2) consider how the system contributed to a larger system). The data shows us that a higher percentage of undergraduate students describe how human action influences concepts in their system map compared to graduate students. To make any conclusions about why we see this relationship in the data, we would need future studies to explore the significance of this relationship with a larger sample size and then determine potential factors that may influence students to include more or less human action connections in their system maps. Regardless, if we want students to include human action connections in their system maps in an assessment, we need to explicitly prompt students to make these connections.

Overall, these findings contribute to our first research question by identifying the skills that undergraduate and graduate students naturally use when constructing systems maps without explicit prompts or scaffolding of ST. After making comparisons between the data among the two groups, we do not see any drastic differences in the types of ST skills that are demonstrated. Instead, we generally see the same trend for graduate students' skills based on what we published for undergraduate students' skills in Chapter 3.3. Therefore, we recommend similar implications for graduate students who are expected to engage in system mapping activities in a graduate chemistry course.

RQ2: To what extent do undergraduate and graduate chemistry students identify parts of a system (e.g., components, relationships, organization, emergent behaviours, system behaviours, boundaries, and granularity)?

We used the same analysis approach in Chapter 3.3 to understand what aspects of ST skills graduate and undergraduate chemistry students demonstrate naturally and where the emphasis needs to be placed when teaching ST skills to students.

Finding 1: *Both undergraduate and graduate student system maps had substantially more concepts and connections at macroscopic levels of granularity than submicroscopic levels.* Figure 15 shows the average number of concepts for each level of granularity within students' system maps. Undergraduate students' system maps have more concepts compared to graduate students' system maps as there is a higher average of concepts for all granularity levels except for the molecular level. However, across the levels of granularity, we see the same trend (more macroscopic concepts than submicroscopic concepts) for both groups (Figure 15).

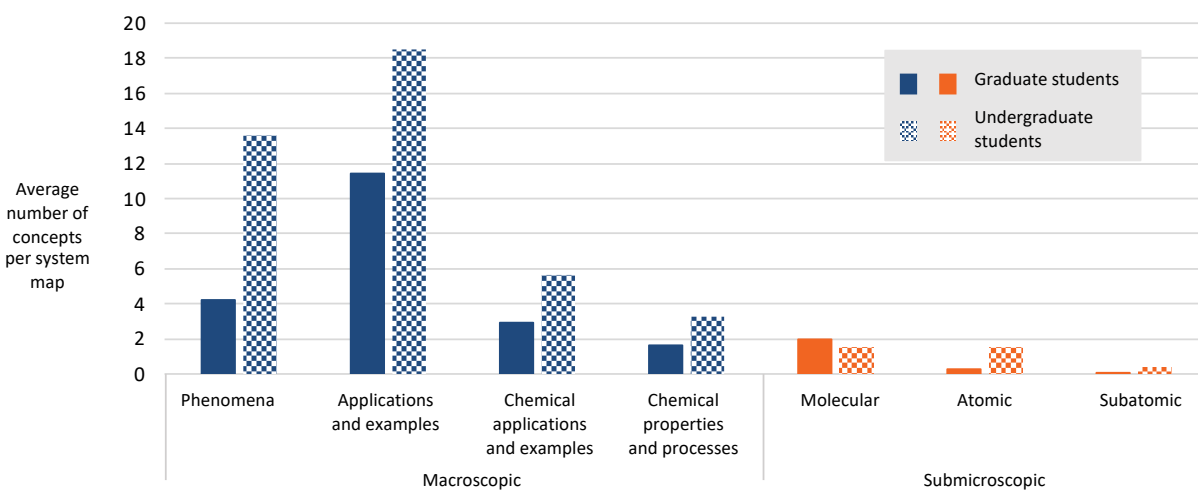


Figure 15. Seven levels of granularity associated with macroscopic and submicroscopic levels used to identify concepts present within undergraduate and graduate students' system maps. The solid colour represents graduate students, and the patterned colour represents undergraduate students.

Figure 16 shows that in both undergraduate and graduate system maps there are limited connections between macroscopic and submicroscopic levels. Graduate students' system maps showed fewer total connections than undergraduate student system maps because there are less participants in that group of students. Therefore, comparisons between groups need to account for the relative amounts of connections by calculating the percentages of each type of connection for both groups. 16%

of the connections in undergraduate students' system maps included connections between submicroscopic and macroscopic concepts and vice versa. Similarly, 20% of the connections in graduate students' system maps include the same connections. However, graduate students included slightly more connections between submicroscopic concepts than undergraduate students.

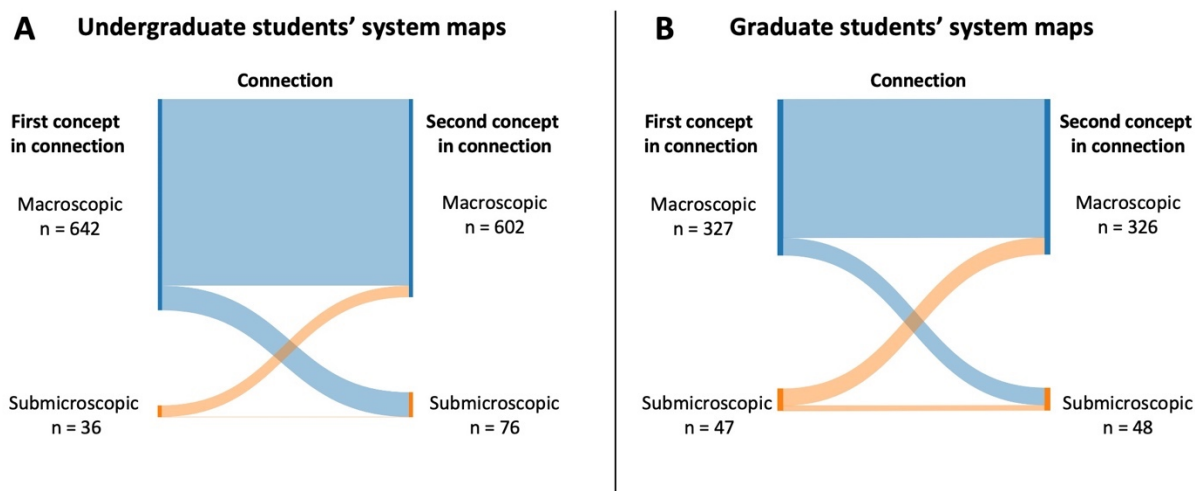


Figure 16. (A) A Sankey diagram indicating the total number of connections made between concepts in the macroscopic (blue) and submicroscopic (orange) levels in all undergraduate students' system maps ($N = 678$). (B) A Sankey diagram indicating the number of connections made between concepts in the macroscopic (blue) and submicroscopic (orange) levels in all graduate students' system maps ($N = 374$). In both Sankey diagrams, the left side indicates the first concept in a connection and the right side is the second concept that is connected (figures produced using SankeyMATIC). The widths represent the frequency of each type of connection. The larger the width, the more frequent the type of connection.

From these comparisons, evidence shows that undergraduate and graduate students make less connections between the macroscopic and submicroscopic levels. Among all connections ($N = 678$) in the 18 undergraduate student system maps, students made 76 connections that began with a macroscopic concept linked to a submicroscopic concept and 36 connections that began with a submicroscopic concept linked to a macroscopic concept. Similarly, among all connections ($N = 374$) in the eight graduate student system maps, students made 48 connections that began with a macroscopic concept linked to a submicroscopic concept and 36 connections that began with a submicroscopic concept linked to a macroscopic concept. These results suggest that both groups need to be explicitly prompted to consider concepts and connections at the submicroscopic level.

Finding 2: Graduate student system maps included more interconnections among concepts compared to undergraduate student system maps, but both groups include few circular loops. Figure 17 shows the average number of connections in undergraduate and graduate students' system maps.

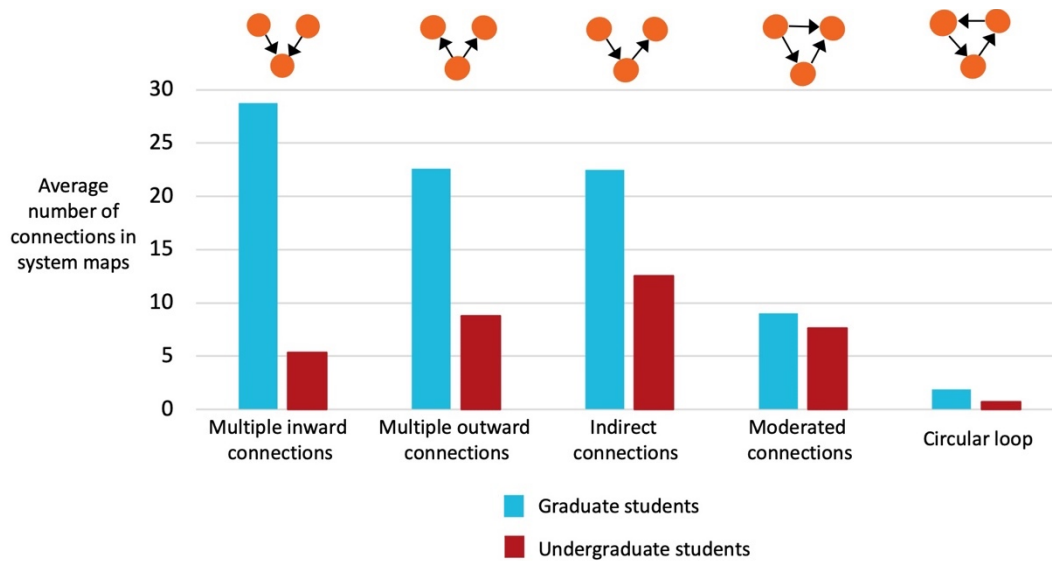


Figure 17. Average number of connections for each type of connection in undergraduate and graduate students' system maps.

The higher averages of multiple inward connections, multiple outward connections, and indirect connections for graduate students' system maps suggests that their maps are denser with connections among concepts. However, the most complex types of connections including moderated connections and circular loops are not frequently shown in system maps amongst both groups. Interestingly, the graduate students' system maps only appear to be more interconnected when merging their written and verbal explanations into their system map. This finding emphasizes that multiple forms of assessment should be used to assess ST skills as there are limitations of system maps. Follow-up interviews were used to gain a deeper understanding of why some students demonstrated more complex connections compared to others. We found that students used different strategies to organize and create their system map, which impacted the types of connections presented. These findings were explained in more detail in Chapter 4. Future research could involve conducting a similar study with a larger sample size, which would enable statistical analyses to identify correlations between complexity of connections and potential factors such as educational background or familiarity with ST. Overall, the comparison of undergraduate and graduate system maps suggests that both groups need to be provided with opportunities to deal with complexity and engage in closed loop thinking (represented by circular loop connections).

Finding 3: *Most undergraduate and graduate students could predict how their system maps changed over time and used descriptive and relational types of reasoning to explain why the map changed* (Figure

18). We analyzed students' responses to the following questions, (1) How does removing the second ideas/concept impact the rest of your system? and (2) Why does removing the second ideas/concept impact the rest of your system? as described in Chapter 3.3. Most students predicted that their system map would partially or fully be impacted when removing a concept from their system map; however, three undergraduates gave no prediction, and one graduate student said their system map would not change. Reasons for the discrepancies in students demonstrating this skill could include how their system map was constructed. Therefore, we further explored how students constructed their system maps by conducting follow-up interviews, described in Chapter 4.

When explaining how their system map would change, at most, students used linear cause-and-effect reasoning except for one graduate student who used multi-component reasoning. Multi-component reasoning considers how the influence of one concept would impact multiple concepts through cause-and-effect relationships.

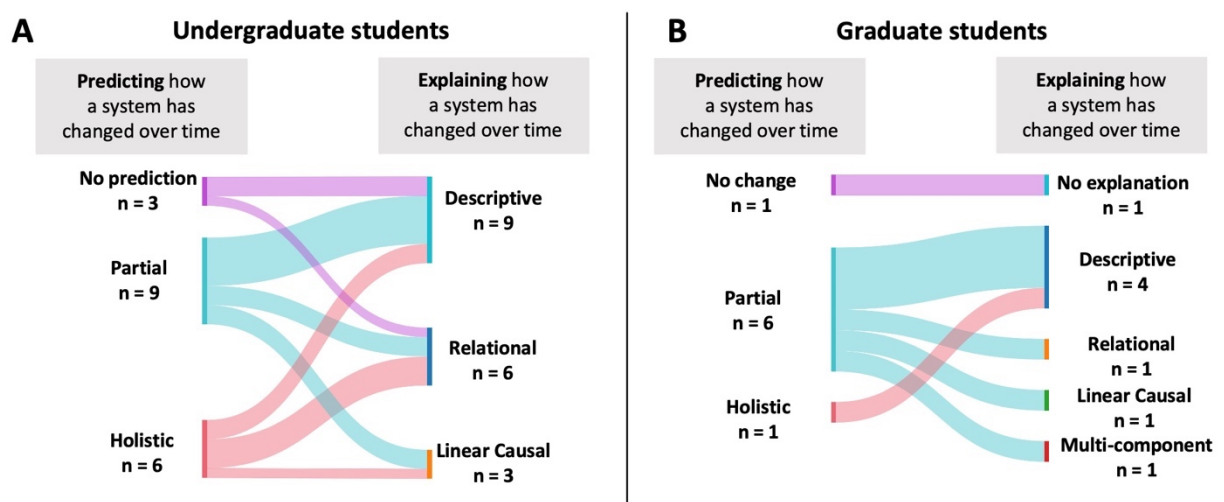


Figure 18. Ways students predicted and explained how their systems changed over time. (A) Undergraduate student predictions and explanations. (B) Graduate students' predictions and explanations.

GS4 predicts that their system map will only partially be changed when removing corn from their system map but, in their explanation, they consider how removing corn would affect several factors (e.g., raising animals, production of various types of fuels) and mentions how removing corn would have a huge effect on the overall field of agriculture (Figure 19).

Predicting how
a system has
changed over time

GS4: "Corn is mainly involved in that (1) it can be grown and (2) it can be used to feed animals - but I don't have it at the centre because animals can be fed by other means (e.g. grass-fed etc). So, it won't change the rest of the map per se, except that it is a huge part of the effect that raising animals has."

**Explaining how
a system has
changed over time**

GS4: "The raising of animals is kind of key in the whole field of agriculture - but only part of the effect of agriculture. So, removing corn would affect the raising of animals, and to a certain extent production of various types of fuels (I think), so would have a huge effect on the field of agriculture as a whole, but isn't the only contributor to the effect of agriculture."

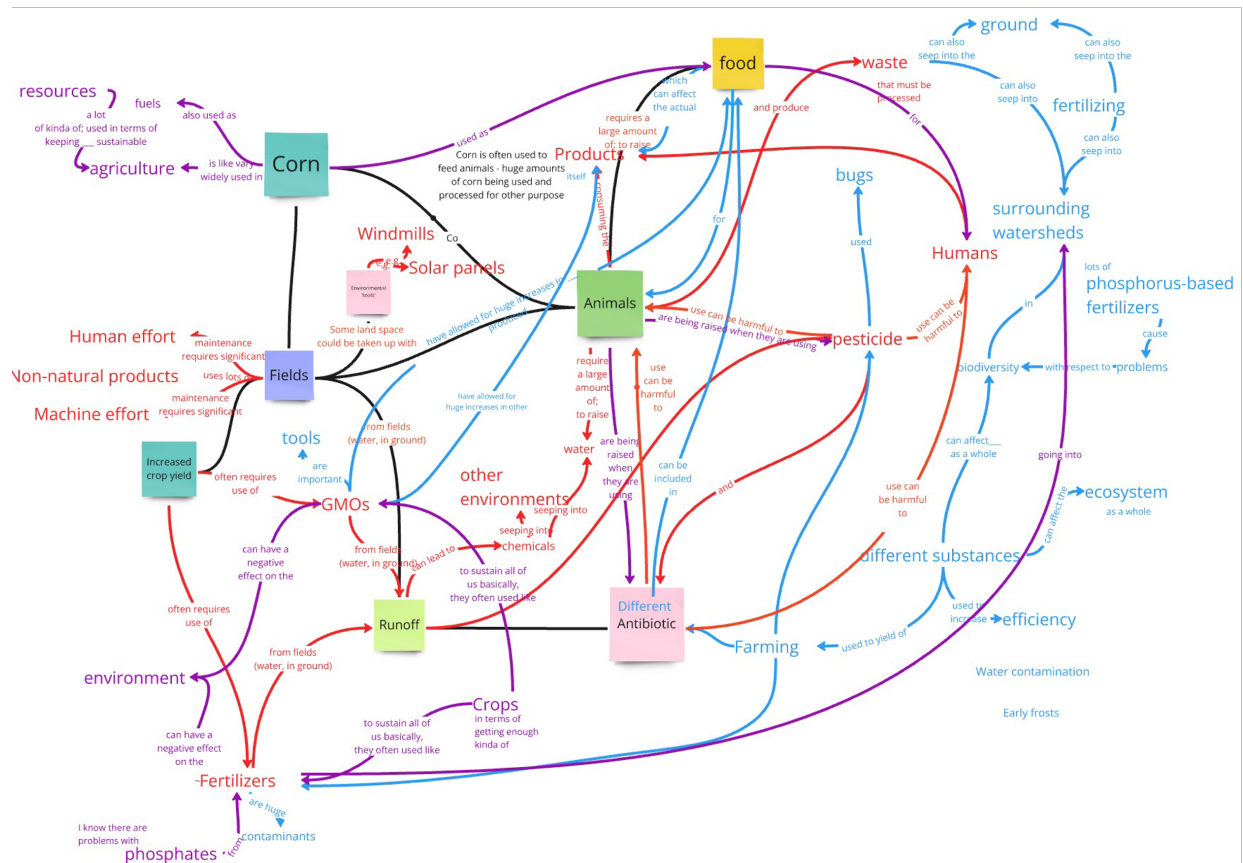


Figure 19. Graduate student 4's (GS4) prediction and explanation for removing their second concept (i.e., corn) from their system map (shown below responses). Black arrows and coloured boxes with concepts represent the students' original work. Red arrows and concepts represent the researcher expanding the students' connections from the original system map. Blue arrows and concepts represent the students' connections from their written responses in the Google Form that they did not explicitly add to their system map. Purple arrows and concepts represent the students' connections from their verbal explanations of their system map.

Here, GS4's responses show that they consider multiple factors that will be affected when removing a concept from their system map, indicating their use of multi-component reasoning. Additionally, they weigh the overall effect of the concept on the greater problem (i.e., the effect of agriculture) which is why they predicted their system map would partially change rather than holistically. In their explanation

of how their system map changes, GS4 elicits the holistic effect of the change. Other graduate students would also address the interconnectedness of their system map in their responses but would only indicate that part of their system map would be affected. However, based on the limitations from this study, we still do not understand why some students at similar educational levels (i.e., graduate versus undergraduate) demonstrate higher levels of reasoning while others do not. Our data does not indicate what students can or cannot achieve as we did not explicitly teach students these skills prior to the ST intervention. Future studies could further investigate potential factors that might influence how students engage in modes of reasoning and draw upon prior literature exploring modes of reasoning in other contexts.

Overall, our findings may suggest the importance of prompting additional reasoning for students' predictions on how their system maps might change over time as well as placing emphasis on teaching multi-component reasoning to help students consider multiple factors in their explanations.

Finding 4: Undergraduate and graduate system maps had a breadth of connections but did not include human connections to the underlying chemistry (Figure 20).

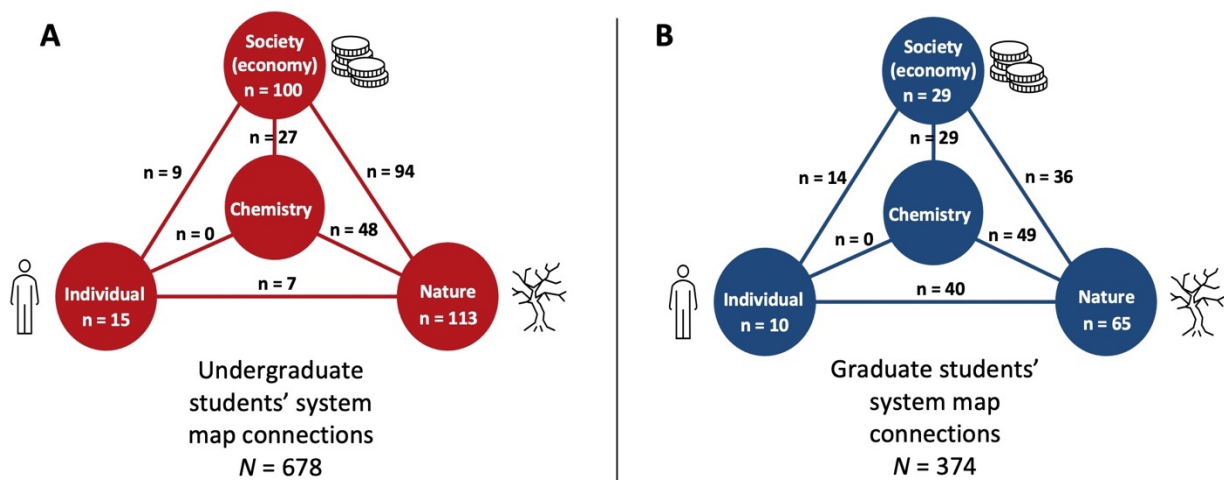


Figure 20. (A) Undergraduate students' system map connections to society, individual, and nature contexts. (B) Graduate students' system map connections to society, individual, and nature contexts.

We found graduate students were able to demonstrate the breadth of connections by making links to other contexts but did not make any connections that involved human impact on chemistry or vice versa. This finding is the same as what we found in our analysis of undergraduate students' system maps in Chapter 3.3. Therefore, as suggested in our manuscript, if students are expected to consider the

impact of human activity on chemistry concepts and topics in system mapping activities, then educators need to explicitly connect chemistry to the lives of the students.

3.4.5 Limitations

Due to the limited sample size, we were only able to make qualitative interpretations from the data and could not measure the influence of chemistry experience quantitatively. Therefore, future studies are needed to explore this relationship with a larger sample size and the design on an experimental study. Additionally, we did not measure the accuracy of students' understanding of the concepts and connections of the topic on climate change due to the scope of this study. Future studies will need to explore how expertise and experience in chemistry influences students' conceptual understandings of the system being studied.

3.4.6 Conclusions

This qualitative analysis investigated the ST skills undergraduate and graduate students do and do not naturally demonstrate during ST tasks, to understand where to place emphasis on teaching ST skills in a chemistry course. We were interested in determining the differences and similarities between how undergraduate and graduate students demonstrated ST skills naturally to understand if experience in chemistry influenced the types of ST demonstrated.

We found that graduate students demonstrated ST skills very similarly to undergraduate students. Graduate and undergraduate students demonstrated most of the 11 ST skills when engaging with the ST tasks, but both demonstrated skills related to behaviours over time and emergence less frequently. Based on this finding, we can hypothesize that experience with chemistry between undergraduate and graduate degree programs may not influence students' abilities to demonstrate ST skills. Therefore, we suggest if students are expected to demonstrate ST skills in a task, both groups need to be explicitly scaffolded and provided with prompts to help them demonstrate certain ST skills.

When further investigating the extent graduate students demonstrated the 11 ST skills, the same themes were uncovered from our analysis of undergraduate student skills, with a few small differences. Both undergraduate and graduate student system maps had substantially more concepts and connections at macroscopic levels of granularity than submicroscopic levels, suggesting that all students need to be explicitly prompted to consider concepts and connections at the submicroscopic level. Without considering these levels of granularity, we found undergraduate students' system maps on average had more concepts compared to graduate students' system maps. However, when looking at the types of connections, graduate student system maps on average included more interconnections among

concepts compared to undergraduate student system maps (e.g., fewer concepts but more connections between these concepts). Both groups did not include many complex connections (e.g., moderated connections or circular connections suggesting the need to focus on these aspects of ST skills in the chemistry classroom).

Most undergraduate and graduate students could predict how their system maps changed over time and used descriptive and relational types of reasoning to explain why the map changed. Some students' explanations would mention the interconnectedness of their system map but would not explicitly explain the multiple factors involved. Therefore, in ST tasks that expect students to explain behaviours of their system maps, both undergraduate and graduate students need to be explicitly taught and prompted to engage in multi-component reasoning.

Lastly, we found that undergraduate and graduate system maps had a breadth of connections but did not include human connections to the underlying chemistry. Therefore, in both undergraduate and graduate chemistry classrooms, educators need to make explicit connections to human dimensions when teaching chemistry concepts to students.

Overall, the findings from this analysis suggest that when teaching ST skills to students, explicit scaffolding and prompting of ST skills need to be provided for both undergraduate and graduate students.

3.4.7 References

- (1) *United Nations' Sustainable Development Goals*. <http://sustainabledevelopment.un.org/> (accessed 2022-12-16).
- (2) 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>.
- (3) Orgill, M.; York, S.; MacKellar, J. Introduction to Systems Thinking for the Chemistry Education Community. *J. Chem. Educ.* **2019**, 96 (12), 2720–2729. <https://doi.org/10.1021/acs.jchemed.9b00169>.
- (4) Hmelo-Silver, C. E.; Pfeffer, M. G. Comparing Expert and Novice Understanding of a Complex System from the Perspective of Structures, Behaviors, and Functions. *Cogn. Sci.* **2004**, 28 (1), 127–138. https://doi.org/10.1207/s15516709cog2801_7.

- (5) Hmelo-Silver, C. E.; Marathe, S.; Liu, L. Fish Swim, Rocks Sit, and Lungs Breathe: Expert-Novice Understanding of Complex Systems. *J. Learn. Sci.* **2007**, *16* (3), 307–331.
<https://doi.org/10.1080/10508400701413401>.
- (6) Gellert, E. Children's Conceptions of the Content and Functions of the Human Body. *Genet. Psychol. Monogr.* **1962**, *65*, 293–411.
- (7) 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.
- (8) Children's Biology: Studies on Conceptual Development in the Life Sciences. In *The Psychology of Learning Science*; Glynn, S. M., Britton, B. K., Yeany, R. H., Eds.; Routledge, 2012; pp 189–212.
<https://doi.org/10.4324/9780203052396-14>.
- (9) Feltovich, P. J.; Coulson, R. L. Learners' (Mis) Understanding of Important and Difficult Concepts: A Challenge to Smart Machines in Education. In *Smart machines in education: The coming revolution in educational technology*; AAAI/Mit Press: Menlo Park, CA, 2001.
- (10) Perkins, D. N.; Grotzer, T. A. Focusing on Dimensions of Causal Complexity to Achieve Deeper Scientific Understanding. In *Paper presented at the annual meeting of the American Educational Research Association*; New Orleans, LA, 2000.
- (11) Feltovich, P. J.; Spiro, R.; Coulson, R. L. The Nature of Conceptual Understanding in Biomedicine the Deep Structure of Complex Ideas and the Development of Misconceptions. In *Cognitive science in medicine: Biomedical modeling*; MIT Press: Cambridge, MA, 1989; pp 113–172.
- (12) Jacobson, M. J. Problem Solving, Cognition, and Complex Systems: Differences between Experts and Novices. *Complexity* **2001**, *6* (3), 41–49. <https://doi.org/10.1002/cplx.1027>.
- (13) Talanquer, V. Progressions in Reasoning about Structure–Property Relationships. *Chem. Educ. Res. Pract.* **2018**, *19* (4), 998–1009. <https://doi.org/10.1039/C7RP00187H>.
- (14) 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](https://doi.org/10.1002/(SICI)1098-2736(199711)34:9<949::AID-TEA7>3.0.CO;2-U).
- (15) *Multiple Representations in Chemical Education*; Gilbert, J. K., Treagust, D., Eds.; Gilbert, E. J. K., Series Ed.; Models and Modeling in Science Education; Springer Netherlands: Dordrecht, 2009; Vol. 4. <https://doi.org/10.1007/978-1-4020-8872-8>.
- (16) 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>.

Chapter 4: “Systems thinking encourages a safe space to offer different perspectives and insights”: Student Perspectives and Experiences with ST Activities

4.1 Introduction to the manuscript in Chapter 4

Our previous research in Chapter 3 helped us understand the types of ST skills chemistry students do and do not naturally demonstrate during ST tasks, which focuses on students’ cognitive domain. This research is beneficial to educators in understanding where they can place more emphasis on teaching ST skills in a chemistry course. But we did not know students’ underlying experiences with demonstrating these ST skills nor how they felt about engaging in the ST activities.

In this chapter, we aimed to further understand how to plan and implement ST activities in chemistry education by investigating students’ experiences of and perspectives toward ST activities. Resistance to new approaches can also apply to students, since learning chemistry is correlated with several factors such as their motivation and attitude toward chemistry,^{1,2} emphasizing the importance of understanding their perspectives and experiences with ST approaches. This research is needed to determine the outcomes of students’ feelings and attitudes when engaging in ST activities in chemistry since attitude is correlated with academic outcomes and learner engagement and has been connected to students’ gender and racial identity.²⁻⁷ Therefore, in this study we investigated the following questions: (1) What are undergraduate and graduate students’ experiences constructing system maps during individual and collaborative ST tasks? and (2) What are undergraduate and graduate student perspectives toward ST tasks in chemistry education?

We used the remaining data from the ST intervention to investigate these questions. However, these questions were not the initial research questions of the study, and the data was not analyzed only once. For context, our initial research questions were: (1) In what ways might collaboration impact the systems created? and (2) How might the creation of these group systems affect participants feeling of inclusion? These research questions were too specific, and the data collected did not inform those questions, leading to analyses that were not very meaningful. We collected a lot of rich, meaningful data from the ST intervention that required us to take a new perspective, rather than starting this project from the beginning and developing a new research design. I like to use the analogy of walking through a maze to describe my experiences working on this project, where I had reached multiple dead ends before finding the right path. This experience can be paralleled with conducting chemistry experiments where one may plan to run an experiment and execute that plan but experience failed experiment after failed

experiment. After some troubleshooting and deeper investigation, one may achieve a successful reaction. As a researcher, these “failed” experiences can be turned into valuable learning opportunities that can make the product or findings more satisfying and significant.

I overcame this challenge in two ways: (1) by gaining different perspectives of the data when working with an undergraduate student, Zahra Lalani, and (2) by taking a different perspective of the data with new research questions. Zahra entered the project with no prior knowledge of ST which was beneficial for the perspectives she brought to our conversations. After we both situated ourselves with the data, we were able to bounce ideas off one another and created research questions that holistically captured the data. The findings of this work became something even greater and more meaningful than what I initially imagined. This research gathers evidence of students’ experiences and perspectives with ST which contribute to best practices for implementing ST and its impact on chemistry education. Additionally, this work is the first to identify the potential impact that sharing and gaining diverse perspectives may have on student learning and engagement as well as equity, diversity, and inclusion (EDI) in chemistry education. Without embracing these experiences and diverse perspectives, we may not have learned about the important implications toward EDI.

Diverse perspectives and experiences are valuable in many different roles and settings – the main message I take away from engaging in this project. Our research is informed and shaped by the different perspectives and experiences of students who participated in this study, the researchers who conducted this study, and the instructors who may use the findings from this study. When prompted carefully, students bring personal experiences, culture, and interests that can shape an inclusive learning environment. Researchers can bring personal interests and questions throughout the research process which helps to shape the overall findings and educators bring important perspectives for putting research into practice. I deeply thank Zahra for the perspectives she brought to this project and her work analyzing students’ perspectives on ST. I also thank all the students I have worked with over the years, Emily Duhart, Christine Paquette, Jade Poirier, and Samira Behroozi, who contributed to prior analyses on this project. It has been such a privilege for me to learn from and share with members of the Flynn Research Group, the education and chemistry education communities, collaborators, mentors, and mentees, throughout my PhD.

While this journey was the longest, I am the proudest of this research. Because of this work, I was invited to give a presentation in the EDI symposium at the 2024 Canadian Chemistry Conference and Exhibition, and present at the 2024 IUPAC International Conference of Chemistry Education. The publication in this chapter has also received the Editor’s Choice recognition in the *Journal of Chemical*

Education,⁸ was featured in the *ACS Publications Education Insider*,⁹ and has been read by over 1300 people.

4.2 References for introduction

- (1) Xu, X.; Lewis, J. E. Refinement of a Chemistry Attitude Measure for College Students. *J. Chem. Educ.* **2011**, *88* (5), 561–568. <https://doi.org/10.1021/ed900071q>.
- (2) Liu, Y.; Ferrell, B.; Barbera, J.; Lewis, J. E. Development and Evaluation of a Chemistry-Specific Version of the Academic Motivation Scale (AMS-Chemistry). *Chem. Educ. Res. Pract.* **2017**, *18* (1), 191–213. <https://doi.org/10.1039/C6RP00200E>.
- (3) Arjoon, J. A.; Xu, X.; Lewis, J. E. Understanding the State of the Art for Measurement in Chemistry Education Research: Examining the Psychometric Evidence. *J. Chem. Educ.* **2013**, *90* (5), 536–545. <https://doi.org/10.1021/ed3002013>.
- (4) Villafañe, S. M.; Xu, X.; Raker, J. R. Self-Efficacy and Academic Performance in First-Semester Organic Chemistry: Testing a Model of Reciprocal Causation. *Chem. Educ. Res. Pract.* **2016**, *17* (4), 973–984. <https://doi.org/10.1039/C6RP00119J>.
- (5) Catsambis, S. Gender, Race, Ethnicity, and Science Education in the Middle Grades. *J. Res. Sci. Teach.* **1995**, *32* (3), 243–257. <https://doi.org/10.1002/tea.3660320305>.
- (6) Else-Quest, N. M.; Mineo, C. C.; Higgins, A. Math and Science Attitudes and Achievement at the Intersection of Gender and Ethnicity. *Psychol. Women Q.* **2013**, *37* (3), 293–309. <https://doi.org/10.1177/0361684313480694>.
- (7) Leslie, S.-J.; Cimpian, A.; Meyer, M.; Freeland, E. Expectations of Brilliance Underlie Gender Distributions across Academic Disciplines. *Science* **2015**, *347* (6219), 262–265. <https://doi.org/10.1126/science.1261375>.
- (8) Szozda, A. R.; Lalani, Z.; Behrooz, S.; Mahaffy, P. G.; Flynn, A. B. “Systems Thinking (ST) Encourages a Safe Space to Offer Different Perspectives and Insights”: Student Perspectives and Experiences with ST Activities. *J. Chem. Educ.* **2024**, *101* (6), 2290–2307. <https://doi.org/10.1021/acs.jchemed.4c00080>.
- (9) ACS Publications Education Insider. In This Issue: Elevating Chemistry, 2024. <https://app.acspubs.org/e/es?s=1913652004&e=5105403&elqTrackId=f02d176c1dae442881549e2ea93464fe&elq=a2c840f9f66e4891894abcb63c5a0860&elqaid=26780&elqat=1&elqcst=272&elqcsid=2263&elqak=8AF50E89D19BE9E695F636E1DD717C7B7055A0C1316EE7D3C2A7A754E56D12941A6F> (accessed 2024-08-06).

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"Systems Thinking (ST) Encourages a Safe Space to Offer Different Perspectives and Insights": Student Perspectives and Experiences with ST Activities

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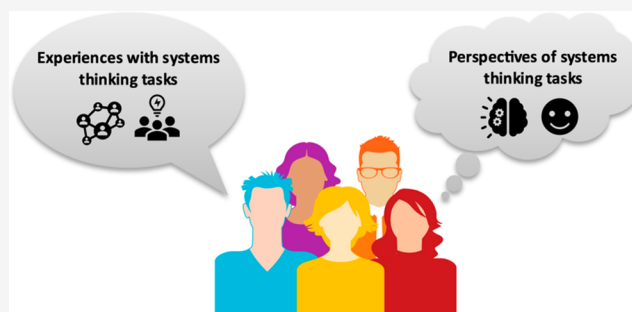
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Supporting Information

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 university 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.

KEYWORDS: *Systems Thinking, Qualitative Analysis, Chemistry Education Research, Diversity and Inclusion, Undergraduate, Graduate, Higher Education, University Learning*



INTRODUCTION

Recent efforts have been directed toward understanding educators' perspectives of systems thinking (ST) in chemistry education;^{1–3} however, students' perspectives (e.g., attitudes, thoughts, perceptions, opinions) 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 on their experiences.^{4–6} Motivation and engagement in learning have been shown to play a role in academic outcomes; therefore, students' experiences (doing ST) and perspectives (attitudes, thoughts, perceptions, and opinions 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

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 these 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 complement 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

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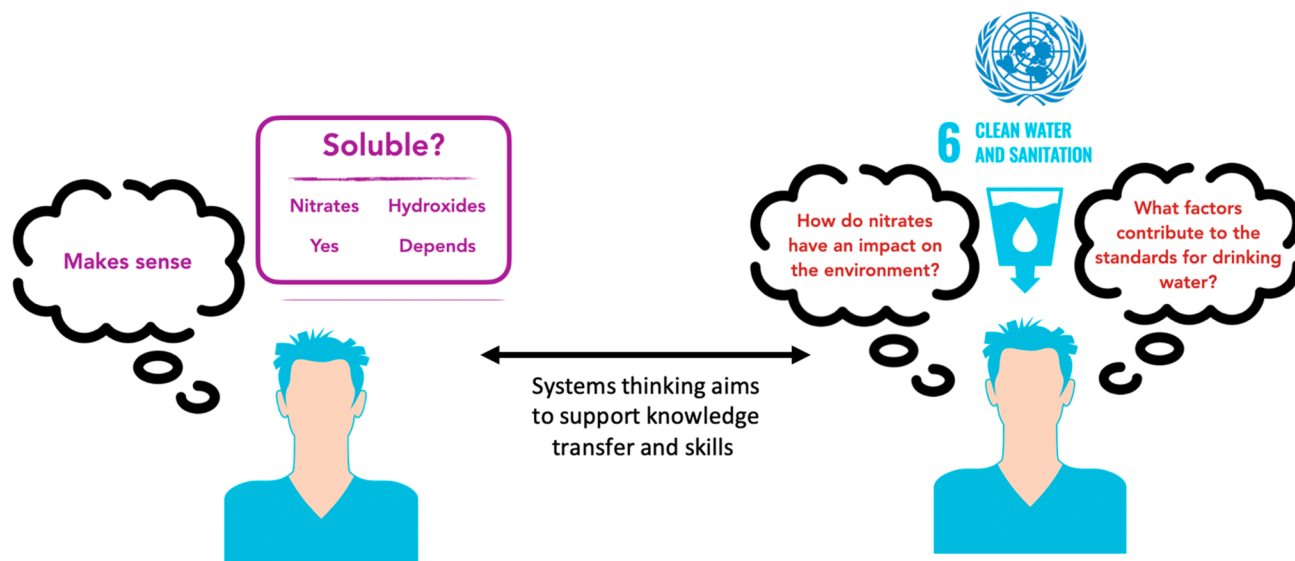


Figure 1. Difference between common teaching approaches and systems thinking approaches with supporting knowledge transfer and skills in chemistry classrooms. Left side: A student learning through a common teaching approach understands specific properties related to chemicals (e.g., nitrates and hydroxides) but may not learn to apply their knowledge in other contexts. Right side: A student learning through a ST approach will identify the impact chemicals have on the environment and understand the factors involved.

skills such as asking questions related to how a chemistry concept or process may contribute to a UN SDG or identifying the intended and unintended consequences of a chemical substance or process.^{8,11–14}

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} The Organization for Economic Co-operation and Development (OECD) Learning Compass 2030 highlights the importance of cognitive and metacognitive skills, social and emotional skills, and physical and practical skills for 21st century skills; all these skills are becoming essential as classrooms and workplaces become more diverse.²⁰ 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.^{21,22} 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 an opportunity to enhance creativity and quality of solutions stimulated by diverse group members.^{23,24}

The proposed benefits of ST from other disciplines have propelled interest in implementing ST in chemistry education.^{25–29} 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: Toward 2030 and Beyond Project:³⁰

Systems thinking is the ability to understand and interpret complex problems (ref 31, 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 32, p 39). 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).^{33–37}

Research suggests that developing ST abilities requires carefully designed instruction with a focus on students' learning and applying ST skills.^{33,38–42} There have been multiple lists of ST skills published in the literature,^{1–3} including several studies in the context of chemistry education.^{17,33} 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 (Figure 2).⁴³

This previous 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 explicitly 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 activities—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:

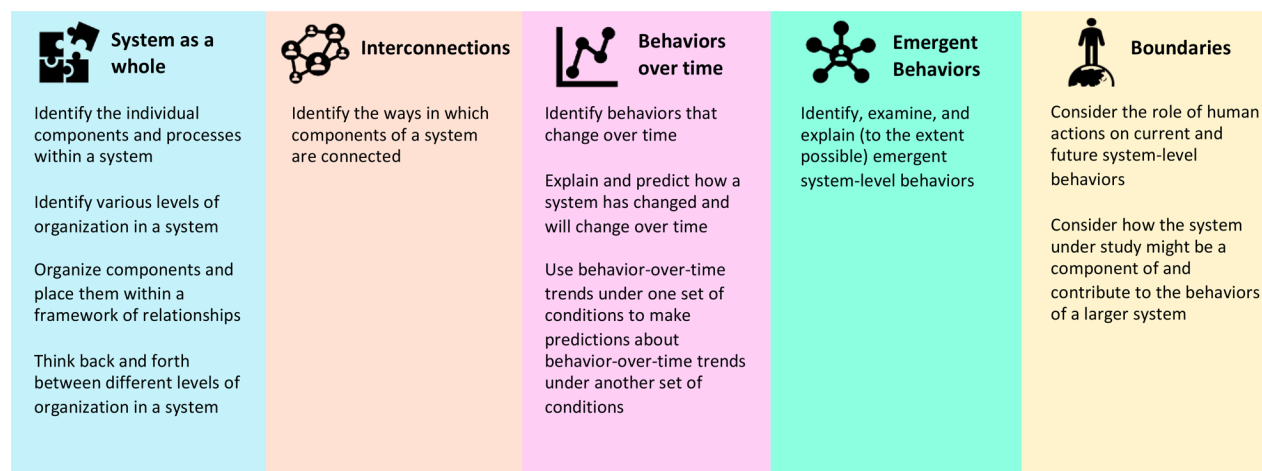


Figure 2. ST skills aligned with five characteristics of STICE chosen for assessment in a previous study. Reprinted from ref 43. Copyright 2023 American Chemical Society.



Figure 3. Design of the ST intervention and interviews used for this study.

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 toward 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 effectively 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 18 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 S1.1.

Data Collection

We designed and implemented a ST intervention and interviews, previously described in this *Journal*,⁴³ 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 preactivity with cognitive and affective instruments, (2) three ST tasks, and (3) a postactivity 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 3). Details of the cognitive and affective instruments are provided in S1.2.

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)⁴⁴ 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 postactivity that asked participants how ST might affect their classmates'

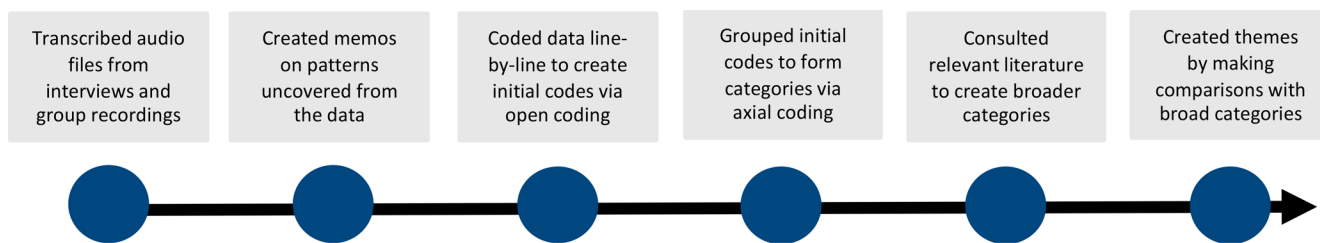


Figure 4. Overview of steps for qualitatively analyzing interview, group task recording, and ST question response data.

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 in the literature (details in S3).^{45,46} 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 min).

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 S1.2).

Data Analysis

We analyzed the data from the interviews, group task recordings, and postactivity responses using well-established methods (Figure 4).^{47,48}

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 postactivity 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 S4 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 S1.5.^{49–52}

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, and (3) retrieve the information as needed (Figure 5).^{43,53} Modern

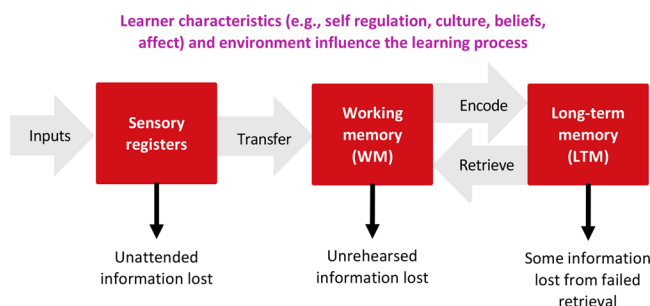
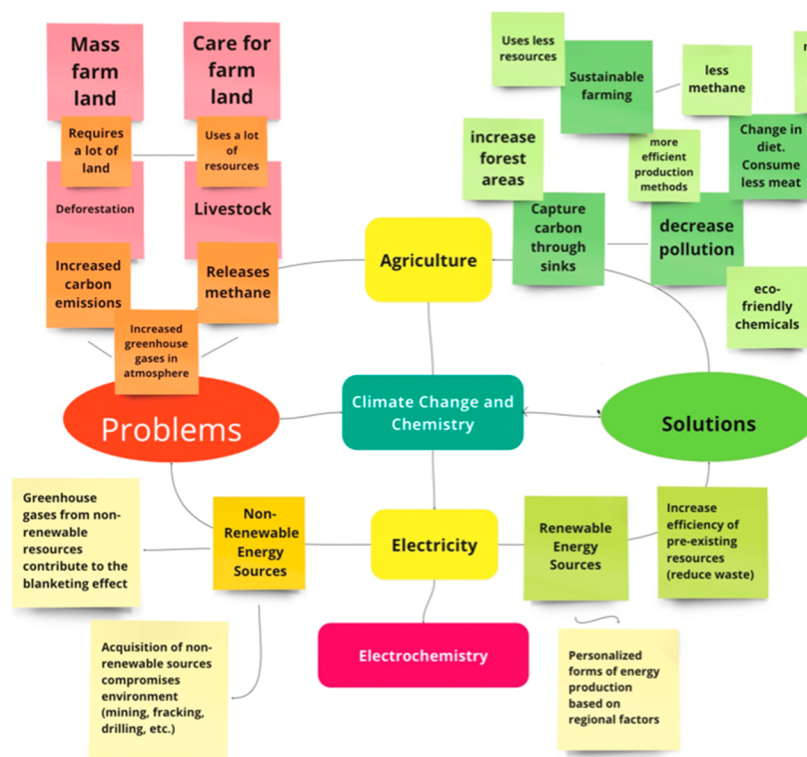


Figure 5. Model of modern information processing theory.

IPT incorporates learners' characteristics (e.g., self-regulation, beliefs, culture, and affect) and the learning environment as these factors greatly influence learning.^{10,43,54}

Researchers predict that educators can harness students' diverse range of prior knowledge in ST approaches beyond just chemistry knowledge.⁵⁵ Therefore, educators need to consider strategies for effectively activating learners' prior knowledge, including learners' experiences, beliefs, and noncontent factors (e.g., attitude, cognitive expectations, motivation, self-concept, self-regulatory strategies, understanding the nature of science).^{10,43,55}

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



U14: "I like what we have because it's very connected and you can see cause -and-effect kind of stuff."

U11: "Yeah, there's a more unified sort of feel, because you can see the different aspects of climate change and chemistry respectively. So, it's kind of interesting. And the whole idea of problems and solutions also kind of adds a sense of duality to the issue."

U12: "Yeah, for sure. Like for the individual ones. I think we just started with a bunch of big words or concepts thrown onto the page, and then just making random connections in between."

U14: "Yeah, I think this made it a lot easier to organize your thoughts and having two diagrams to base the information off of was really helpful, because you could think about things that you didn't think about at first."

U11: "Yeah, different perspectives on the same issue. That's always helpful"

Figure 6. Conversation among three undergraduate students in the group task with their system map. U11 mentions there is a unified feel of the concepts in the group system map. U12 and U14 agree and indicate other benefits of creating a group system map.

maps.⁴³ Relevant prior knowledge from the learner's long-term memory impacts how that knowledge is stored and organized.⁵⁶ 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.⁵⁵ 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.⁵⁷ 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.

Sociocultural theory explains how the learning environment plays an integral role in cognition.^{55,58} This theory stresses the importance of culture and social interaction in developing and shaping individuals, with an essential application being peer collaboration.^{58–60} The Supporting Information has more information about how these theories are embedded into the ST tasks of the ST (S1.4).

Researchers have previously proposed that ST can be used to engage students in social, historical, and cultural interactions.⁵⁵ 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.⁵⁵ 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 came 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 6).

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 good 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 6 communicate why it is important for educators to embrace diversity in the chemistry classroom. Students from diverse backgrounds can share their ideas and experiences with others in activities to facilitate educational outcomes such as cultural knowledge and awareness, recognizing the complexity of issues and learning to work with different kinds of people.^{61,62} 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.^{63–67} 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 7).

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.⁶⁸ When engaging in systems

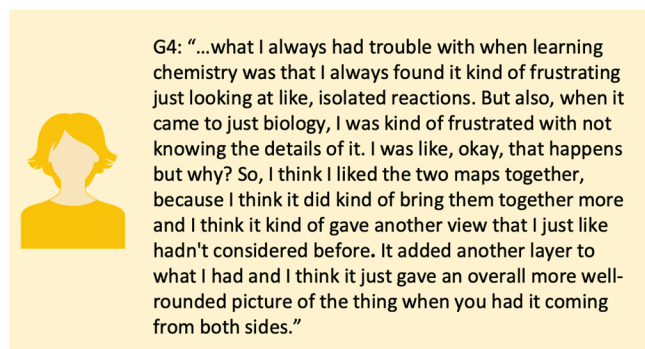


Figure 7. G4 mentioned they gained an additional perspective from their partner's system map that helped bridge concepts from chemistry and biology to see a well-rounded view of the topic.

mapping exercises, students valued the opportunity to reflect on multiple aspects of chemical processes.⁶⁸ 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 8).

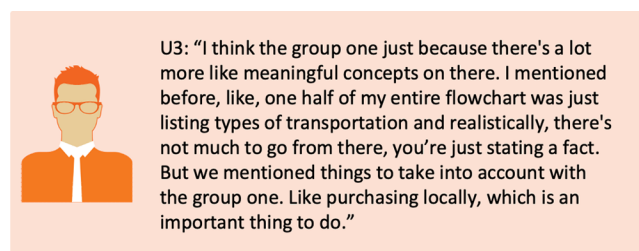


Figure 8. U3 stated that the group system map contains more meaningful concepts compared to their system map as they were stating facts.

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 9).

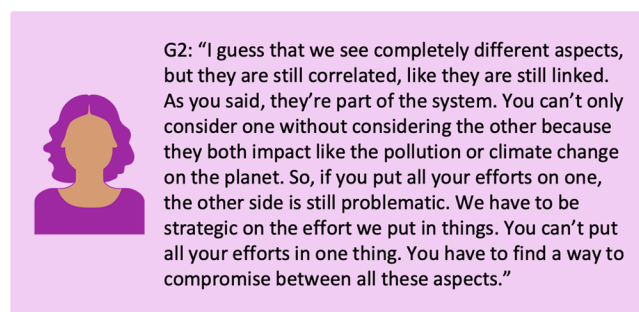


Figure 9. G2 identified that they saw different aspects of a topic compared to their partner but realize they could not consider one aspect without considering the other; therefore, both aspects needed to be considered when making efforts to address the problem (e.g., climate change or pollution).

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.^{63,69–72}

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 10).

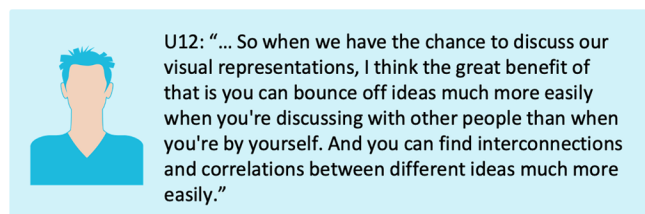


Figure 10. U12 mentioned that, when given the chance to discuss their system maps in a group, they could bounce off ideas allowing them to identify interconnections between different ideas more easily.

Collaboration also helped participants with the ST skill: *identifying emergence*. Emergence involves a property or behavior resulting from interactions between system parts, rather than an individual part.^{33,43} 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. Some participants identified a more significant meaning or importance for constructing their system map after they identified a new topic, as previously shown (Figure 8). Six of the ten groups constructed their system maps from scratch, starting with a new topic from their conversation (Figure 11A). The four remaining groups copied one or both of their system maps, placed them side by side and tried making connections between the concepts (Figure 11B).

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 may not appropriately be activated, or their working memories may be overloaded.^{58,73,74}

Collaborative approaches have been found to provide social, psychological, academic and assessment benefits for students' learning and skill development.^{75–77} Learning theories support that social and cultural interactions are critical for stimulating developmental processes, fostering cognitive growth, and transforming students' learning experiences.^{58,59} 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 12). 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 need to explicitly scaffold and prompt students to think about finer granularity levels (e.g., molecular) related to the topic of interest.⁷⁸

A few participants mentioned that having different ideas and topics as a group made it more challenging to make some connections (G1, Figure 12). One participant indicated that considering more perspectives and concepts from their partner can be overwhelming (G4, Figure 12).

These student experiences highlight potential challenges that educators should be mindful of when integrating collaborative ST tasks into a course. To ease students' feelings of being

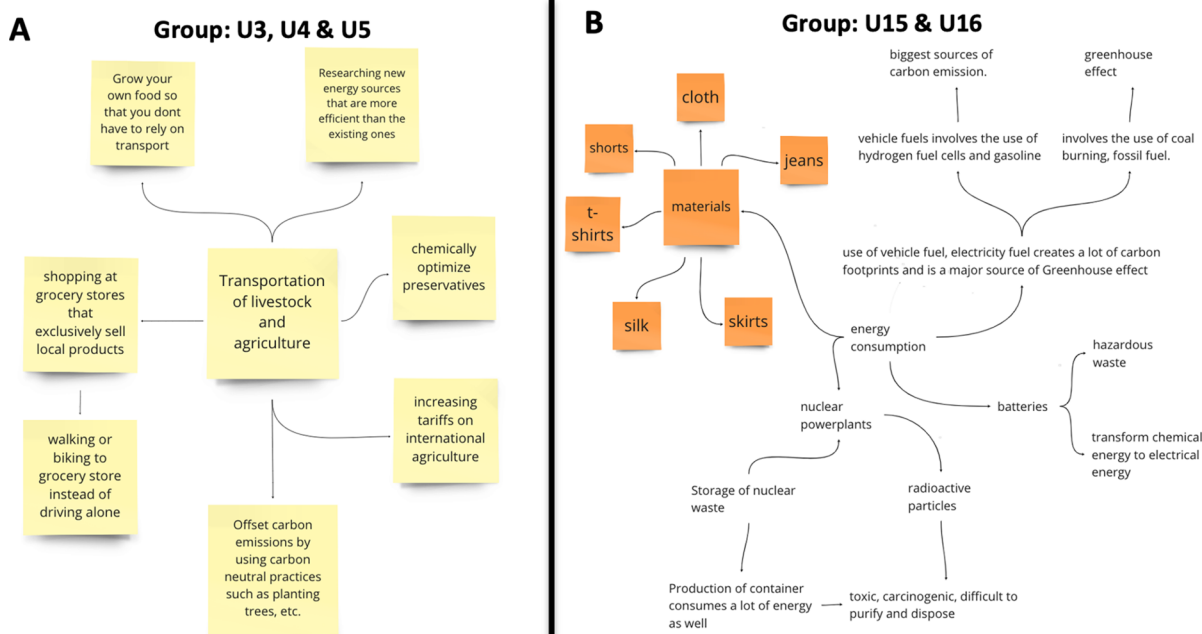


Figure 11. Examples of group system maps. (A) A group system map constructed using a new, emergent topic. (B) A group system map constructed by placing individual maps side by side and making a connection.

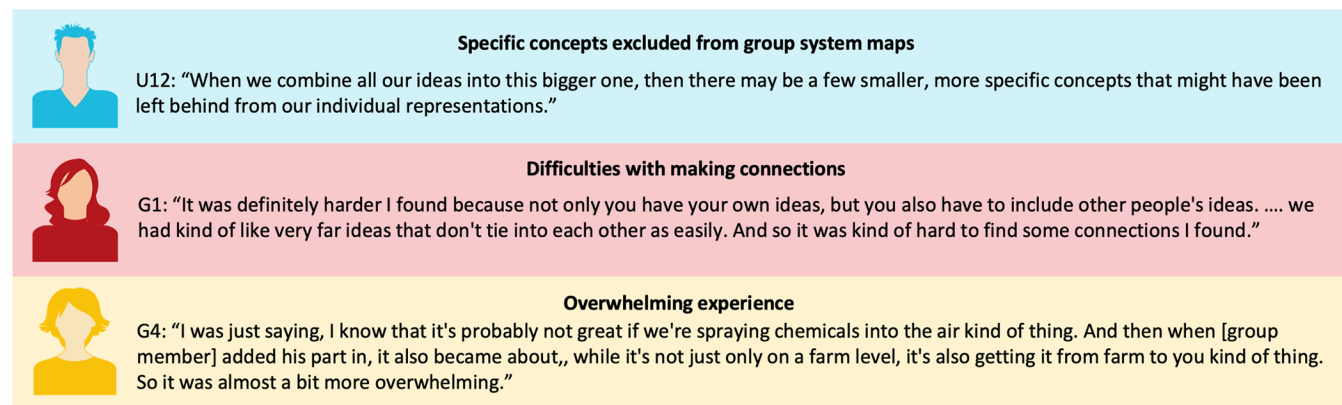


Figure 12. Examples of group map challenges and disadvantages reported by participants (U12, G1, and G4).

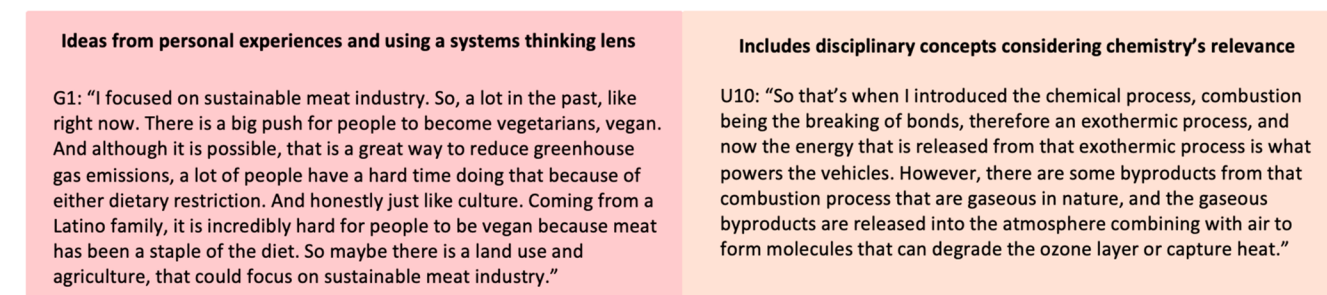


Figure 13. Examples of approaches used to add concepts by participants (G1 and U10).

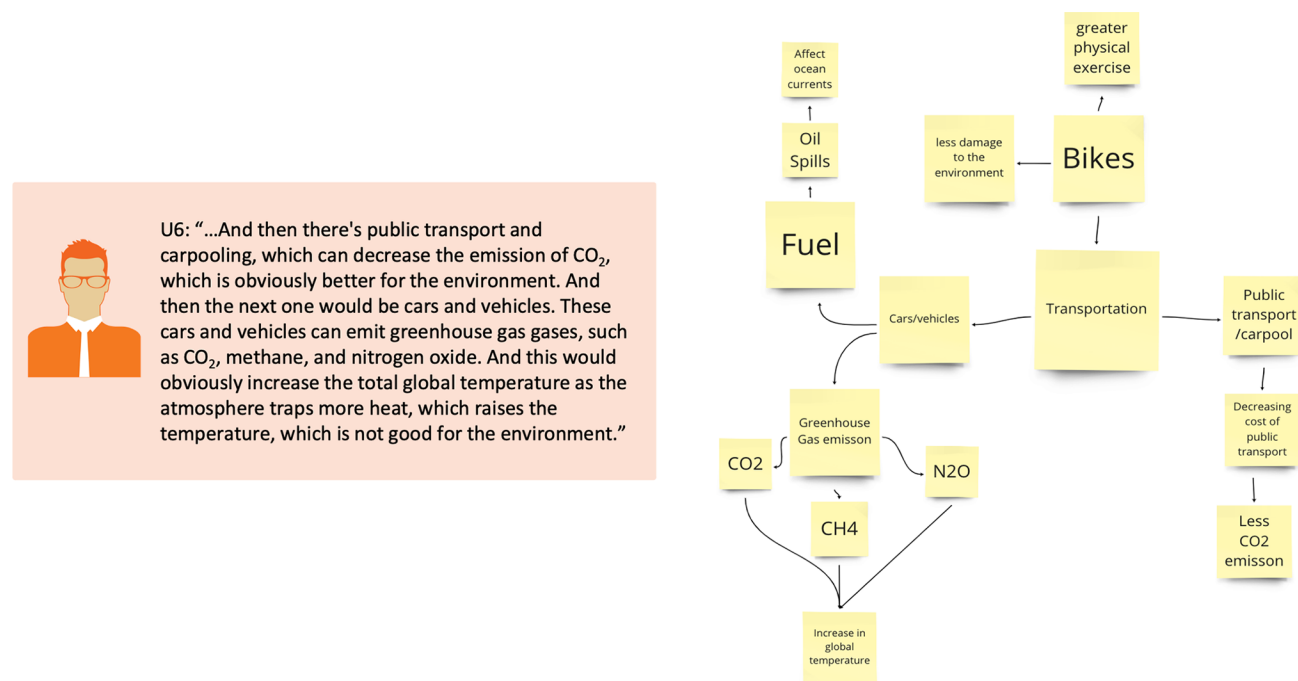


Figure 14. U6 mentioned molecular concepts when explaining their system map but did not explain or show the sources of how the molecules are produced or how they increase the global temperature. U6's system map is on the right.

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 and can be guided through the use of scaffolding tools and feedback approaches.^{79–81} Educators should consider ways to include those who are neurodivergent

(e.g., autistic, Attention Deficit Hyperactivity Disorder, dyslexia) as working in a group can be overwhelming and ineffective.⁸² Equity, diversity, and inclusion (EDI) researchers have suggested that student–instructor interactions in an active learning environment can also promote students' success.⁷⁰ 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.⁷⁰

Overall, the findings presented in this theme suggest 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 common teaching approaches in chemistry education are used.⁸³ 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.^{84–90} 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 13).

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 nitrogen oxides) 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 14).

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.⁴³ 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.^{91–96} 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.^{97,98} As a result, students can get confused and lack motivation toward chemistry.⁹³

Participants also indicated they had difficulty using chemistry concepts to make connections. One participant mentioned that they could have focused more on the chemistry aspects of their topic but they learned about climate change from the news or conversations with people who do not focus on the finer scientific details (Figure 15).



U12: “When we combine all our ideas into this bigger one, then there may be a few smaller, more specific concepts that might have been left behind from our individual representations.”

Figure 15. U12 realized they could focus more on the chemistry aspects of their topic, but they did not learn about the scientific details and suggested that we need to learn about the chemistry behind everyday concepts in chemistry courses.

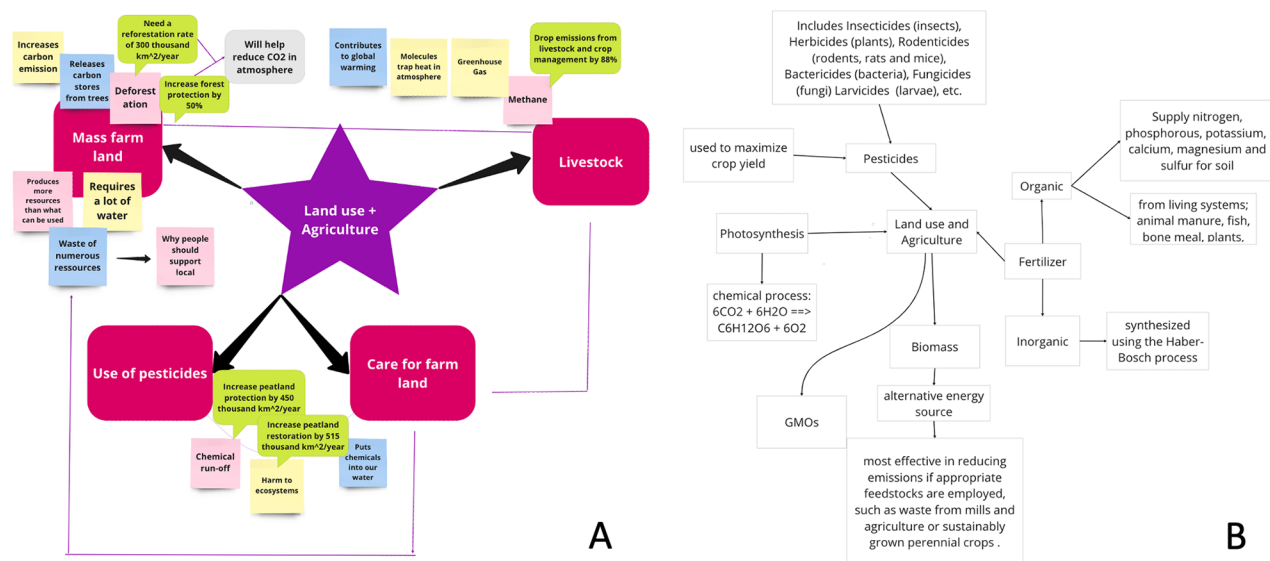
Our findings show that participants may not have the opportunity to learn the scientific details of climate change. Educators may teach chemistry concepts related to climate change, but it may not be taught meaningfully to the learner or the connections between chemistry and climate change are not made 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.

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 oversimplifying their understanding of complex phenomena.^{99–104} 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, the economy, the environment, and human health.^{8,12,102,108–110} When implementing a ST activity in a chemistry course, in the context of a specific global issue, the educator needs to (1) explicitly highlight the role that chemical concepts and processes play in the global issue and (2) provide opportunities for students to use, articulate, and demonstrate ST skills in new contexts. Future ST studies could focus on using the Model of Educational Reconstruction to analyze students’ understanding of the chemistry in socio-environmental issues (e.g., climate change) when engaging in a ST approach and their perspectives on the learning process and subject matter to guide the integration of socio-scientific issues into chemistry courses.¹⁰⁵

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 16a), while other participants only added ideas related to their main topic (no explicit branching into subtopics) (Figure 16b).

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



U14: "So basically, my four main points were mass farmland... Livestock, and which also kind of connects them as farmland because you need the land for the livestock, care for farmland and use of pesticides...and so obviously, all of them have negative effects...Overall, most of them just create things that are damaging either to the atmosphere, like greenhouse gases, or things that go into our water systems."

U5: "I did land use and agriculture and I didn't have really good groupings. But I like I started with photosynthesis for like a chemical because it's a chemical process...And then there's like pesticides, which are, like used to maximize crop yield... And then for fertilizer I included organic and inorganic... And then I found biomass was the most related renewable energy source, and...It's most effective in reducing emissions, if like the appropriate feedstocks are used, like waste from mills and agriculture or supplying growth renewal crops."

Figure 16. Example of individual system maps with different organizational strategies and participants' explanations of how they constructed their system maps. (A) 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) U5's system map, which is organized by starting with their main topic and then adding ideas related to this topic (no explicit branching into subtopics).

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 sub-systems 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.¹⁰⁶ 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 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 17).



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 17. U12 indicated their system was created based on instinctual organization (i.e., how they categorize all ideas naturally) rather than a designed organization and they would change their system map for educational purposes.

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 (S2.2). 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 18).

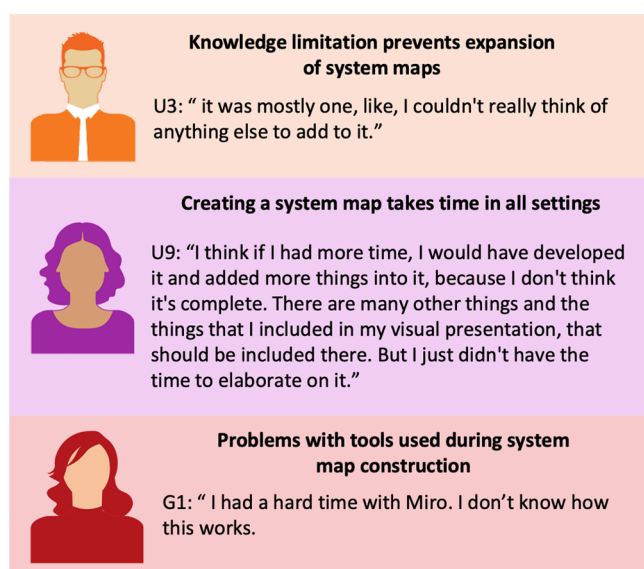


Figure 18. Examples of knowledge, time, and technology skill limitations reported by participants (U3, U9, and G1).

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 18). 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 18).

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.^{107–109} 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.^{99,110} 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.⁹⁹ Providing additional scaffolding to support the use of online technologies and the 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 (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 helpful 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 19).

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.^{111–113} Some research-

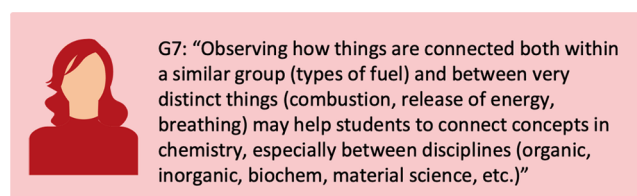


Figure 19. G7 mentioned that ST may help students connect concepts in chemistry, especially between disciplines.

ers 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.^{12,83,114} To arrive at 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 nonscience-based professionals.^{11,115} Therefore, chemistry educators may consider how to integrate interdisciplinary learning outcomes in their courses 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 toward a future purpose or goal. Additionally, one participant indicated that a ST activity could promote critical thinking (Figure 20).

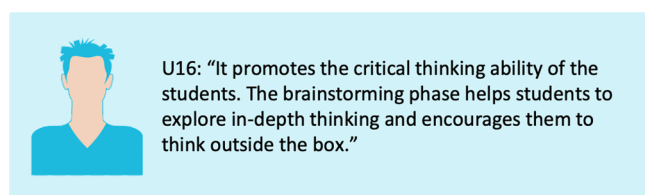


Figure 20. U16 mentioned that the brainstorming phase of the ST activities could help students engage in thinking deeper about concepts and promote critical thinking.

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.¹¹² Critical thinking is often experienced as a byproduct of interdisciplinary learning.¹¹² 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.^{21,22}

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 postactivity 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 21). G4 also indicated their interest with engaging in the ST tasks (S4.3, 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 21).

Collectively, these findings show that ST may improve student engagement and interest in chemistry when students can connect chemistry to their personal lives and interests. Increased student engagement and interest have been reported

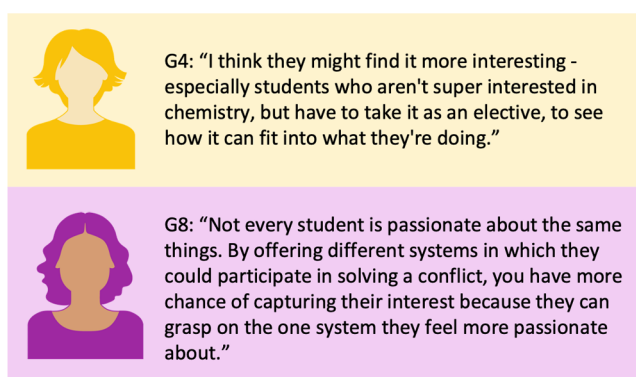


Figure 21. Participants G4 and G8 mentioned ST might help capture students' interests, including students who are not initially interested in chemistry.

as a potential benefit of ST as it encourages students to become personally involved in what they are learning.^{17,116,117} 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 22).

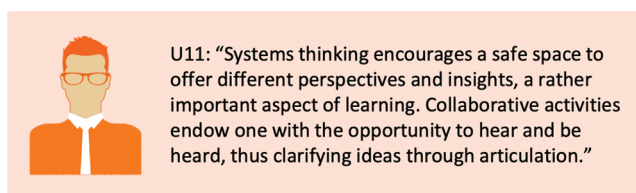


Figure 22. U11 mentioned that collaborative ST activities encourage a safe space to offer different perspectives and insights which they believe is an important aspect of learning.

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 had not considered before and how they view things in different ways (Figure 23).

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.¹¹² Our findings identify the potential significance of perspective taking for students and therefore should be considered in the design of ST activities.

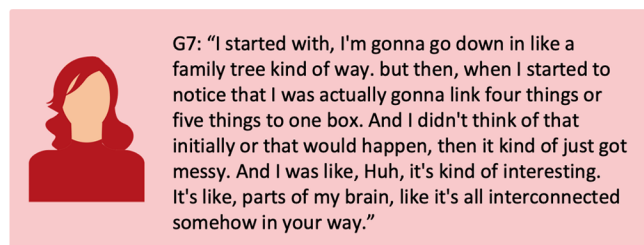


Figure 23. G7 mentioned that, when creating their system map, they noticed they started making many connections to one concept, which is not how they were initially thinking about the concepts and connections.

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 24). Educators also believe that ST may expose students to less mainstream career paths they may not have considered.¹¹⁴ 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 24). Lastly, participants' responses indicated ST may provide relevance to their own or others' lives (personal relevance) (U9, Figure 24).

These findings show the potential for ST to make connections that are relevant to students—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.

IMPLICATIONS FOR TEACHING AND RESEARCH

This work is one of the first in chemistry education research focused on ST 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.

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 among concepts—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

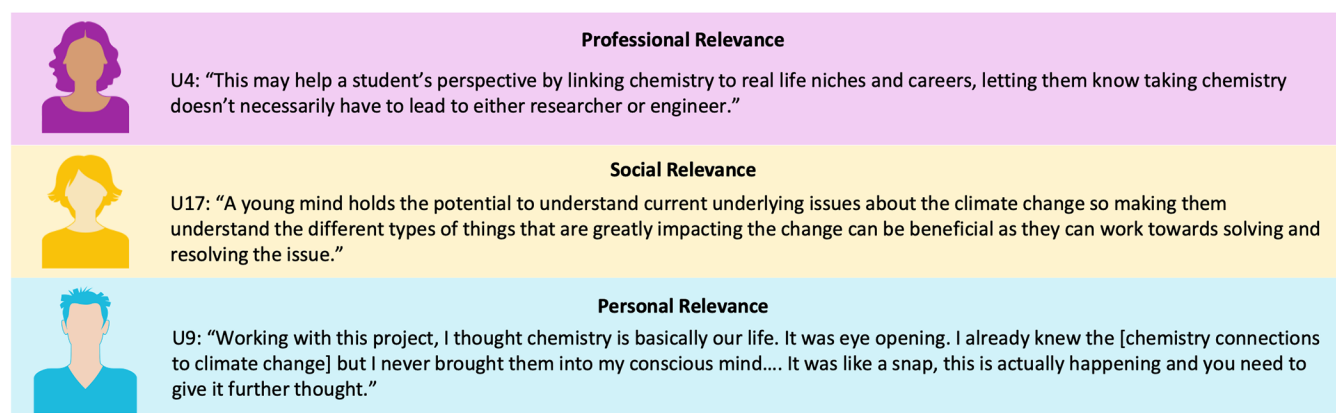


Figure 24. Examples of participants' quotes on professional, social, and personal relevance (U4, U17, and U9).

Table 1. Summary of Recommendations for ST Instruction in Chemistry and Future Chemistry Education Research, Based on This Study's Findings

Findings from This Study	Recommendations for ST Instruction in Chemistry Education
Participants recognized and appreciated different perspectives and ideas from group members.	Include explicit opportunities for students to share and gain diverse perspectives.
Participants indicated they had difficulty or were uncertain about using chemistry concepts to make connections.	Explicitly highlight the role that chemistry concepts and processes play in the global issue.
Participants may not have the opportunity to learn scientific details of climate change.	Provide opportunities for students to use, articulate, and demonstrate ST skills in new contexts.
Participants believed that engaging with ST can (1) allow students to relate real-life to chemistry concepts, (2) teach students the many applications that chemistry has in the real world, and (3) help students connect concepts in chemistry to other disciplines.	Consider integrating interdisciplinary learning outcomes to elicit ST and critical thinking skills.
Participants who organized their system map with subtopics made more interconnections compared to those who did not.	If using systems maps in a ST activity, consider using a guided approach to teach students how to construct system maps.
Participants' intended purpose of constructing their system map limited the number of concepts or connections they included in participants' system maps.	Consider the different educational purposes for using system map (e.g., presentation, brainstorming for personal learning, and navigating connections) and avoid assessing the system map directly.
Participants reported that time, knowledge, and technology skills limited the construction of their individual and group system maps.	Provide scaffolding to support the use of online technologies and development of technology skills. Consider timing require to complete ST activities or assessments. Allow students to develop adequate domain knowledge in class so that they can integrate this with their prior knowledge, experiences, and interests.
Findings from This Study	Recommendations for Future Chemistry Education Research
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).	Investigate if using a ST approach can support active thinking, cognitive sophistication, and intellectual engagement when students with diverse perspectives interact.
While collaborating, participants recognized and appreciated different perspectives. The findings from 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.	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 lead to academic achievement.

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 perspectives—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 and at one institution. Future studies would be needed to determine student perspectives and experiences when ST activities are implemented within a course and in different educational and institutional contexts to further explore the opportunities and challenges of ST implementation.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemed.4c00080>.

Details about the methods, data analysis, and themes as well as the code books and ST interview questions (e.g., themes, description of themes, categories, and representative quotes) for this study ([PDF](#); [DOCX](#))

ST intervention ([PDF](#); [DOCX](#))

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Author Contributions

A.R.S., P.G.M., and A.B.F. conceived the project and designed the initial research questions and methods. A.R.S. collected the data. S.B. analyzed the first round of graduate interview data. A.R.S. and Z.L. revised the research questions to better align with the data collected. A.R.S. analyzed students' data collected from the interviews and verbal explanations from the group task. Z.L. analyzed students' written responses from the ST question in the postactivity. All authors discussed the analysis, results, and conclusions. Z.L. wrote the first draft of the Results and Discussion for RQ2. A.R.S. wrote the first draft for all other sections of the manuscript. A.R.S., A.B.F., and P.G.M. edited and revised the manuscript.

Notes

The authors declare no competing financial interest.

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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**, 99 (7), 2474–2483.
- (2) Hurst, G. A.; Slootweg, J. C.; Balu, A. M.; Climent-Bellido, M. S.; Gomera, A.; Gomez, P.; Luque, R.; Mammìno, 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.
- (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.
- (4) Hutchison, J. E. Systems Thinking and Green Chemistry: Powerful Levers for Curricular Change and Adoption. *J. Chem. Educ.* **2019**, 96 (12), 2777–2783.
- (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.
- (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.
- (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.
- (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.
- (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.
- (11) Matlin, S. A.; Mehta, G.; Hopf, H.; Krief, A. One-World Chemistry and Systems Thinking. *Nat. Chem.* **2016**, 8 (5), 393–398.
- (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.
- (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.
- (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; DOI: 10.1016/B978-0-12-817418-0.00002-4.
- (15) Rainie, L.; Anderson, J. *Future of Jobs and Jobs Training*; Pew Research Center, 2017; <http://www.pewinternet.org/2017/05/03/the-future-of-jobs-and-jobs-training/>.
- (16) World Economic Forum. *The Future of Jobs: Employment, Skills and Workforce Strategy for the Fourth Industrial Revolution*; 2016; https://www3.weforum.org/docs/WEF_FOJ_Executive_Summary_Jobs.pdf.
- (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.
- (18) Overton, T.; McGarvey, D. J. Development of Key Skills and Attributes in Chemistry. *Chem. Educ. Res. Pr.* **2017**, 18 (3), 401–402.
- (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.
- (20) OECD. *OECD Future of Education and Skills 2030: Skills for 2030*; 2019; https://www.oecd.org/education/2030-project/teaching-and-learning/learning/skills/Skills_for_2030_concept_note.pdf (accessed 2024–03–12).
- (21) National Research Council. *Assessing 21st Century Skills: Summary of a Workshop*; National Academies Press: Washington, D.C., 2011; DOI: 10.17226/13215.
- (22) National Research Council. *Research on Future Skill Demands: A Workshop Summary*; National Academies Press: Washington, D.C., 2008; DOI: 10.17226/12066.
- (23) Child, S.; Shaw, S. Collaboration in the 21st Century: Implications for Assessment. *Res. Matters Camb. Assess. Publ.* **2016**, No. 22, 17–22.
- (24) 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>.
- (25) 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.
- (26) 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.
- (27) Frank, M. Engineering Systems Thinking and Systems Thinking. *Syst. Eng.* **2000**, 3 (3), 163–168.
- (28) 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.
- (29) 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.
- (30) *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).
- (31) 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.
- (32) Talanquer, V. Some Insights into Assessing Chemical Systems Thinking. *J. Chem. Educ.* **2019**, 96 (12), 2918–2925.
- (33) 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.

- (34) 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.
- (35) 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.
- (36) 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.
- (37) Marton, F. Describing and Improving Learning. In *Learning Strategies and Learning Styles*; Springer Science+Business Media: New York, NY, 1988; pp 53–82.
- (38) 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.
- (39) 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.
- (40) 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.
- (41) 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.
- (42) Hmelo, C. E.; Holton, D. L.; Kolodner, J. L. Designing to Learn About Complex Systems. *J. Learn. Sci.* **2000**, 9 (3), 247–298.
- (43) 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.* **2023**, 100 (5), 1763–1776.
- (44) Mahaffy, P. G.; Martin, B.; Hoffman, M.; MacDonald, R. P.; Elgersma, A. K.; Lasola, K.; Gagnon, A.; Ciezki, A.; Tilstra, M.; Vanderweken, L.; Keeler, T.; Schwalfenberg, A.; Vandenbrink, D.; Zondervan, J. *Design Our Climate Simulation*; <https://climatesolutions.kcvs.ca> (accessed 2022–12–15).
- (45) Patton, M. Q. Qualitative Interviewing. In *Qualitative Research & Evaluation Methods*; SAGE Publications, Inc.: Thousand Oaks, CA, 2015; pp 421–517.
- (46) Creswell, J. W. *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*; Pearson: Boston, MA, USA, 2012.
- (47) 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.
- (48) Boyatzis, R. E. *Transforming Qualitative Information: Thematic Analysis and Code Development*; Sage Publications, Inc: Thousand Oaks, CA, US, 1998.
- (49) Lincoln, Y. S.; Guba, E. G.; Pilotta, J. J. *Naturalistic Inquiry*; Sage: Newbury Park, CA, 1985.
- (50) Saldaña, J. *The Coding Manual for Qualitative Researchers*, 3rd ed.; SAGE Publications, Inc.: Thousand Oaks, CA, 2016.
- (51) Creswell, J. W.; Miller, D. L. Determining Validity in Qualitative Inquiry. *Theory Pract.* **2000**, 39 (3), 124–130.
- (52) Guba, E. G.; Lincoln, Y. S. Competing Paradigms in Qualitative Research. *Handb. Qual. Res.* **1994**, 105–117.
- (53) Schunk, D. H. *Learning Theories: An Educational Perspective*, 6th ed.; Pearson Education Inc: Boston, MA, 2012; Vol. 5.
- (54) 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; DOI: 10.1037/13273-004.
- (55) Pazicni, S.; Flynn, A. B. Systems Thinking in Chemistry Education: Theoretical Challenges and Opportunities. *J. Chem. Educ.* **2019**, 96 (12), 2752–2763.
- (56) 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.
- (57) Bretz, S. L. Novak's Theory of Education: Human Constructivism and Meaningful Learning. *J. Chem. Educ.* **2001**, 78 (8), 1107.
- (58) Schunk, D. H. *Learning Theories: An Educational Perspective*, 6th ed.; Pearson: Boston, 2012.
- (59) Vygotsky, L. S. *Mind in Society*; Cole, M., Jolm-Steiner, V., Scribner, S., Souberman, E., Series Eds.; Harvard University Press, 1978; DOI: 10.2307/j.ctvjf9vz4.
- (60) 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.
- (61) King, J. Asked students to share ideas and experiences with others whose backgrounds and viewpoints differ from their own; IDEA; <https://www.ideaedu.org/idea-notes-on-instruction/asked-students-to-share-ideas-and-experiences-with-others-whose-backgrounds-and-viewpoints-differ-from-their-own> (accessed 2024–02–27).
- (62) Meacham, J.; McClellan, M.; Pearse, T.; Green, R. Student Diversity in Classes and Educational Outcomes: Student Perceptions. *Coll. Stud. J.* **2003**, 37 (4), 627–642.
- (63) Goethe, E. V.; Colina, C. M. Taking Advantage of Diversity within the Classroom. *J. Chem. Educ.* **2018**, 95 (2), 189–192.
- (64) 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.
- (65) 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.
- (66) 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.
- (67) 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.
- (68) 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.
- (69) 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.
- (70) 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.
- (71) 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.
- (72) 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.
- (73) 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.
- (74) Novak, J. D. *Learning, Creating, and Using Knowledge: Concept Maps as Facilitative Tools in Schools and Corporations*, 2nd ed.; Routledge, 2009;
- (75) Panitz, T. The Motivational Benefits of Cooperative Learning. *New Dir. Teach. Learn.* **1999**, 1999 (78), 59–67.
- (76) Johnson, D. W.; Johnson, R. T. *Cooperation and Competition: Theory and Research*; Interaction Book Company: Edina, MN, USA, 1989.
- (77) Laal, M.; Ghodsi, S. M. Benefits of Collaborative Learning. *Procedia - Soc. Behav. Sci.* **2012**, 31, 486–490.

- (78) 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.
- (79) Hermanns, J.; Schmidt, B. Developing and Applying Stepped Supporting Tools in Organic Chemistry To Promote Students' Self-Regulated Learning. *J. Chem. Educ.* **2019**, *96* (1), 47–52.
- (80) Hermanns, J. How Should Stepped Supporting Tools Be Designed to Support Non-Major Chemistry Students While Solving Tasks in Organic Chemistry - Results of a Think-Aloud Study. *Prog. Sci. Educ. PriSE* **2020**, *1* (3), 9–25.
- (81) Taber, K. *Chemical Misconceptions: Prevention, Diagnosis and Cure: Theoretical Background*; Royal Society of Chemistry, 2002; Vol. 1.
- (82) Spaeth, E.; Pearson, A. A Reflective Analysis on How to Promote a Positive Learning Experience for Neurodivergent Students. *J. Perspect. Appl. Acad. Pract.* **2023**, *11* (2), 109–120.
- (83) 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.
- (84) 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.; Peacock, B. R.; Pickett, S. B.; Slager, D. L.; Caviedes-Solis, I. W.; Stanchak, K. E.; Sundaravandan, 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. U. S. A.* **2020**, *117* (12), 6476–6483.
- (85) 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), No. es5.
- (86) 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.
- (87) 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. U. S. A.* **2014**, *111* (23), 8410–8415.
- (88) 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), No. e0268620.
- (89) Valdez, C. J.; Kelp, N. C. Student Perceptions of Inclusive Pedagogy in Undergraduate STEM Classrooms. *J. Microbiol. Biol. Educ.* **2023**, *24*, e00097–23.
- (90) Johnson, K. M. S. Implementing Inclusive Practices in an Active Learning STEM Classroom. *Adv. Physiol. Educ.* **2019**, *43* (2), 207–210.
- (91) Talanquer, V. Progressions in Reasoning about Structure–Property Relationships. *Chem. Educ. Res. Pract.* **2018**, *19* (4), 998–1009.
- (92) 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.
- (93) Johnstone, A. H. Teaching of Chemistry - Logical or Psychological? *Chem. Educ. Res. Pr.* **2000**, *1* (1), 9–15.
- (94) 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.
- (95) 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; DOI: 10.1007/978-1-4020-8872-8_9.
- (96) 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.
- (97) Talanquer, V. Macro, Submicro, and Symbolic: The Many Faces of the Chemistry “Triplet”. *Int. J. Sci. Educ.* **2011**, *33* (2), 179–195.
- (98) Johnstone, A. H. Macro- and Microchemistry. *Sch. Sci. Rev.* **1982**, *64*, 377–379.
- (99) 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.
- (100) 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.
- (101) 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.
- (102) Royer, J. M. Theories of the Transfer of Learning. *Educ. Psychol.* **1979**, *14* (1), 53–69.
- (103) Chemistry education must change to help the planet: here's how. *Nature* **2022**, *604* (598); DOI: 10.1038/d41586-022-01109-z.
- (104) 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.
- (105) Duit, R.; Gropengießer, H.; Kattmann, U.; Komorek, M.; Parchmann, I. The Model of Educational Reconstruction – a Framework for Improving Teaching and Learning Science. In *Science Education Research and Practice in Europe*; Jorde, D., Dillon, J., Eds.; SensePublishers: Rotterdam, 2012; pp 13–37; DOI: 10.1007/978-94-6091-900-8_2.
- (106) King's Centre for Visualization in Science. SOCKit; <https://applets.kcvs.ca/sockit/index.html> (accessed 2023–11–24).
- (107) 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.
- (108) 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>.
- (109) Gillett-Swan, J. The Challenges of Online Learning: Supporting and Engaging the Isolated Learner. *J. Learn. Des.* **2017**, *10* (1), 20–30.
- (110) 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.
- (111) You, H. S. Why Teach Science with an Interdisciplinary Approach: History, Trends, and Conceptual Frameworks. *J. Educ. Learn.* **2017**, *6* (4), 66.
- (112) Mathews, L. G.; Jones, A.; Szostak, R.; Repko, A. Using Systems Thinking to Improve Interdisciplinary Learning Outcomes: Reflections on a Pilot Study in Land Economics. *Issues Integr. Stud.* **2008**, *26*, 73–104.
- (113) Fisher, D. Reflections on Teaching System Dynamics Modeling to Secondary School Students for over 20 Years. *Systems* **2018**, *6* (2), 12.

(114) 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.

(115) Constable, D. J. C. Green and Sustainable Chemistry – The Case for a Systems-Based, Interdisciplinary Approach. *iScience* **2021**, 24 (12), No. 103489.

(116) Sweeney, L. B. How Is This Similar to That?. *Systems Thinker*. <https://thesystemsthinker.com/how-is-this-similar-to-that/> (accessed 2024-02-27).

(117) 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.

Chapter 5: Using systems thinking to evaluate misinformation

5.1 Introduction to the research presented in this chapter

Misinformation and disinformation are the biggest short-term risks based on risks perception data from the World Economic Forum's Global Risk Report 2024.¹ Misinformation is the unintentional dissemination of inaccurate information while disinformation is the dissemination of inaccurate information with the intention to cause harm. Like, business leaders, researchers need to constantly take a critical stance on the trends and patterns of information to create new ideas for improving current processes, products, and services. The same can be true in the context of education – critically identifying areas that need investigation of educational approaches to help solve educational challenges. The initial projects we created for my degree are the research described in Chapters 2 to 4. Chapter 5 introduces a new plan of a ST project that was created to extend our ST research.

Exploring ST as a potential approach for evaluating false information emerged from a brainstorming discussion on future ST research with Dr. Alison Flynn and Dr. Peter Mahaffy. We discussed current global issues where educational research could be most beneficial for the educational and chemistry education communities. The rapid increasing concern of artificial intelligence (AI)-generated disinformation and spread of misinformation on global issues such as the coronavirus (COVID-19) pandemic brings attention to the need for educational research on approaches that can equip citizens and students with the knowledge and skills to identify and evaluate information and be proficient with AI technology.²⁻⁴

I have been personally invested in conducting research on misinformation and disinformation as most of my degree has been completed during the COVID-19 pandemic and over these years, I have observed the spread of false information about COVID-19 and distrust in mitigation practices, including vaccination, through the news and conversations with people.^{5,6} Mistrust in science and scientists can have profound impacts on people's health as shown by those who believe vaccines are harmful.⁷ These beliefs not only endanger the lives that hold this idea but also the greater population that depends on high levels of vaccination for their health.² Vaccine hesitancy and denial are likely responsible for a large portion of COVID-19 deaths.⁸

Extending our contributions to the ST literature, we also wanted to explore the impact of a ST approach based on what we learned from our previous studies by expanding our research in a classroom setting. Dr. Flynn showed trust in me by giving me the freedom to create and run a ST activity that explored a misinformed topic in her Organic Chemistry II course. While I had a lot of experience teaching high school students and TAing undergraduate students, this was my first opportunity to teach in a

university-level chemistry class, which meant a great deal to me, and I thank Dr. Flynn for trusting me throughout the process. This opportunity served as a pilot for creating the design of the new ST study described in this chapter.

I designed an experimental study to explore the impact of a ST approach for evaluating false science information. Unfortunately, I ran out of time in my degree to obtain IRB approval and follow through with the study as I was focused on completing the final analysis in Chapter 4. Fortunately, a then-undergraduate student, Kathryn Bruyere, who worked on the educators' perspectives ST project in Chapter 2, was interested in working on this new ST project for her Honours project. She has used the design as a starting point and will now continue to pursue this research in her graduate studies. I am beyond thrilled to see this project be carried out. I am even happier to see that she has shaped the design of the study to focus on her interests (e.g., looking at misinformation about vaccines with students in a biochemistry course). Designing and outlining this project has given me a boost of confidence in becoming a chemistry education research professor. The fact that this project will be used as a graduate project makes me believe that my knowledge and experiences are valuable. Thank you, Dr. Flynn, for continuously believing in me, even during the many times I did not believe in myself.

The following chapter has multiple sections: (1) a proposal of ST's role for evaluating false science information in the form a draft commentary (Chapter 5.2.1), (2) an in-depth literature review on the current approaches used to evaluate science information (Chapter 5.2.2), and (3) an overview of the plan for conducting the project (Chapter 5.3 to 5.6), outlining theoretical frameworks, research questions and goals, methods, and next steps for this new ST project. Dr. Alison Flynn (corresponding author), Dr. Peter Mahaffy, and I are the authors of the draft commentary titled, "Systems thinking as a potential approach for evaluating false science information" found in section 5.2.1. The rest of the chapter 5.2.2 to 5.7 is not part of the commentary but rather other areas I have intellectually contributed toward developing the research project. We created the commentary as a call to action for science education research needed to investigate ST's role in evaluating misinformation, as no research has explored this topic and there is urgent need to help citizens and scientists develop the knowledge and skills to navigate through our modern, digital world.

5.2 Introduction

5.2.1 Systems thinking as a potential approach for evaluating false science information

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Immediate action is required to address the growing fake news phenomenon as its consequences are increasingly dangerous at both individual and collective levels: manipulated voting, people who do not vaccinate their children, people who do not wear masks during a pandemic, people that try suspicious treatments, denial of anthropogenic climate change, and portrayal of ethnic groups as enemies.^{9,10} The dissemination of deliberate and nondeliberate false information has been increasing in recent years (i.e., disinformation and misinformation, respectively), particularly due to the influence of social media and the growing use of artificial intelligence.^{11–13} Science has been brought into the spotlight from the COVID-19 pandemic and has led many scientists to disseminate information in popular media. An infodemic (i.e., a large amount of information, accurate or not) was facilitated by social media leading to interference with disease prevention policies, undermining public trust in science, and hindering individuals capacity to make evidence-informed choices.^{9,14} In response, the World Health Organization has been training professionals to combat misinformation from this infodemic.¹⁵ Additionally, Generative Artificial Intelligence (GenAI) has been beneficial for helping citizens and scientists summarize and generalize large amounts of existing information and has made progress toward achieving Sustainable Development Goal 4, ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all.¹⁶ However, GenAI systems contain pitfalls such as reporting misleading information when their systems are trained and operate on biased or unreliable data.¹³ Thus, the user of GenAI needs to assess the quality of information produced.

Several promising initiatives are being explored, including large-scale automated approaches,¹⁷ increased responsibility by social media services,¹⁸ and scientists speaking out when seeing false

information being presented on social media.^{9,19} However, when trying to correct misleading claims on social media, scientists are often constrained by word limits on the platforms, which leads to approaches such as persuasive appeal, the use of quotes from scientific authority figures or illustrating single-study results as “anecdotal evidence”.²⁰ Scientists are also competing with preprints (i.e., scientific papers that are not peer-reviewed by a journal) that convey anecdotal evidence, making it even more difficult to differentiate reliable, cumulative scientific evidence from the temporary nature of preprint findings. While these approaches can help mitigate the spread of inaccurate information, they do not provide a long-term solution for generating a more scientifically literate society.⁹ A long-term solution needs to help people develop the abilities to critically examine information and reach a judgement about its trustworthiness based on evidence and reasoning.⁹

Education is considered an essential part of the long-term solution, in which evidence-based approaches are needed to equip learners with the knowledge, skills, and tools to be able to critically examine and assess information.^{9,14,21,22} Students are a large population who are actively present on social media networks; therefore, are highly exposed to dis- and misinformation. Science lessons are particularly suitable for examining misinformation and generating knowledge about chemical phenomena (e.g., COVID-19 pandemic).¹¹ However, formal science education does not typically address the issue of misinformation or teach science media literacy.³ Additionally, the range of science communication practices for students (both inside and outside the classroom) is small — limited to visiting extracurricular learning sites or visits of professionals and experts at school.¹¹ There are also only a few programs that have trained students to communicate with non-experts.¹⁴ Another critical aspect of these approaches is to facilitate student identification of fake news.¹¹ Students' prior knowledge plays a decisive role in identifying fake news, which must be generated by suitable practices.¹¹ While there is widespread agreement for increased science literacy across institutions, the literature does not clearly articulate what it means to be science literate in the 21st century and what skills students need to be equipped with to protect themselves against misinformation.⁴

Science educators have an important role in equipping the next generations of students and citizens with the skills to deal with dis- and misinformation and learn how to evaluate it using evidence-based approaches. Systems thinking (ST) has emerged in the literature as an approach for addressing sustainability challenges through Green and Sustainable Chemistry practices.^{23,24} These global challenges are multidimensional problems of complex systems that require a systemic lens for generating solutions. Therefore, addressing these global challenges requires analyzing the complex system as a whole rather than just looking at a collection of its parts, examining the factors involved in the system along with their

interactions, and how those interactions lead to system behaviours that change over time.²⁵ Scholars in scientific communication have argued that if science literacy has a goal of enabling learners to identify misinformation on complex scientific issues, science literacy must extend beyond traditional ways of thinking about and learning science.⁴ Approaches should be focused on the entire “science information lifecycle”, which involves understanding how science information is generated by the scientific community, how the media disseminates this information, and how individuals access, process, and form opinions on that information.⁴

A recent literature review looked at research on COVID-19 and its implications on environmental phenomena from a systems-oriented perspective.²⁴ Selin claims one reason why research on global challenges (e.g., COVID-19) benefits from a systems thinking approach is that “analyses that do not account for systems behavior risk mischaracterizing the pandemic’s impacts, implications, and related causal mechanism.”²⁴ The review found few studies and commentaries focusing on evaluating environmental and sustainability impacts of COVID-19 using a systems lens.²⁴ Not using a systems lens results in scientific journals presenting the effect of COVID-19 and associated pandemic related-policies on the environment separate from its impacts on people and institutions.²⁴ Information on COVID-19 presented in this way has led to people making arguments that COVID-19 has been beneficial for our Earth based on a few selected factors, and some have made claims that restoring the global environment from the effects of anthropogenic activities is possible through temporary shutdowns.²⁴ Applying systems thinking to examine global challenges could help to avoid these types of mischaracterizations.

Inaccurate scientific information is commonly established from global challenges, suggesting that a systems approach could be used in science education to teach students how to evaluate claims in the literature and on social media. Systems thinking has been previously identified as one potential approach that can be used as a tool for modelling misinformation. However, our perspective piece draws toward science students actively using systems thinking skills to evaluate information in different types of media. Systems thinking could be used similar to a fact-checker strategy called lateral reading which involves leaving an unknown website to consult other sources to evaluate the original source.²⁶ However, systems thinking would expand searching for other sources on the same topic by looking at additional factors that could help explain a scientific phenomenon. For example, one approach could involve using misinformation on a global challenge to introduce a science lesson. The educator could share two opposing claims from the media (e.g., accurate and inaccurate information) and prompt students through a set of questions to identify the accurate scientific information. Students would use the scientific knowledge learned from the course and explore additional factors related impacts of the global

issue. Identifying these components and interactions between the components could help students understand the impact of a global challenge more holistically and use reasoning skills to determine the accurate claim.

Considering how systems thinking is currently being used and investigated in science education, no studies to date have looked at the impact of a systems thinking approach for evaluating inaccurate information in a STEM educational setting. Therefore, some questions emerge for science education; (1) To what extent can a systems thinking approach help students evaluate inaccurate science information?, (2) What systems thinking skills do students need to develop to evaluate inaccurate science information?, (3) What are the benefits and drawbacks of a systems thinking approach for evaluating inaccurate science information? and (4) What other strategies in tandem with using a systems thinking approach are required for helping students evaluate inaccurate science information, if at all? Based on educators' perspectives of systems thinking approaches, some educators might argue that there is not enough room in the current curriculum or time to implement such an approach or that a systems thinking approach would extend students' cognitive capacity.²⁷ While these are potential concerns and challenges, empirical investigation is required before making claims on the impact of using systems thinking to evaluate false information.

Science education research on systems thinking could draw on existing analytical approaches for assessing global challenges that have been used in scientific research such as the human-technical-environmental (HTE) systems framework.²⁸ This framework provides analysts from different disciplinary backgrounds to study a common way to advance systems-focused research on sustainability issues. Engaging in the HTE systems framework involves identifying and examining the components, considering the interactions among the components, and providing information that can inform interventions.²⁴ Other scholars have created a framework for conceptualizing science literacy over three dimensions that span the lifecycle of science information.⁴ These dimensions include, (1) civic science literacy skills (e.g., understanding how science is produced and how science relates to broader society), (2) digital media science literacy skills (e.g., understanding how science information appears and moves through media systems), and (3) cognitive science literacy skills (e.g., understanding how people interpret science information when they come across it).⁴ A systems thinking lens could complement these three dimensions for identifying and evaluating misinformation.

Advancements in science education research are needed to investigate systems thinking's role in evaluating misinformation and there is ample opportunity for exploring science literacy skills given the prevalence of misinformation and use of generative AI in the world. Considering the range of complex

global challenges we face in today's society, there is an urgent need to help citizens and scientists develop the skills required to navigate through our modern, digital world. By equipping citizens and scientists with the necessary skills, they will be more prepared to compete for future jobs and better equipped to advise policymakers that shape the direction of governments and institutions globally.

5.2.2 Approaches to evaluate science information in the media

People assume that students are digital natives, equipped with the skills needed to use modern technology effectively, due to being frequently immersed in digital environments.^{2,29,30} However, while it is true that students are comfortable with technology, evidence indicates they are not proficient.² Students of all ages and levels have challenges with evaluating information.^{31,32} Recent research has demonstrated that students are prone to accepting false information from internet resources and trust misinformation in digital media similar to how they trust valid information.^{33,34} Furthermore, research in science education has repeatedly suggested that young students accept claims in science articles without questioning the supporting evidence or reasoning.^{35,36} These studies suggest that students may view scientific claims in media as objective, lacking the ability to examine the evidence supporting these claims. Therefore, science education plays a vital role in providing students with the competencies needed to navigate through and critically evaluate misinformation. The following paragraphs illustrate the work that has been done to help students recognize misinformation and strategies to help students develop digital competencies for evaluating misinformation.

Based on inoculation theory, one approach has been used to neutralize potential misinformation before it is encoded,^{37,38} as it is difficult to correct misinformation once it has been processed.³⁹ Inoculation theory proposes that people can be prepared for potential misinformation by alerting them of potential threats of information before they receive the misinformation.^{38,40} The rationale of this pre-exposure is that by “inoculating” people in this way, they will recognize flawed arguments and dismiss them as deceptive.³⁸ Research has shown that individuals can be made to resist attitude-changing messages or events when they have previously been prepared for the occurrence. Cook et al. (2017) explored the impact of misinformation about climate change and tested several pre-emptive interventions designed to reduce the influence of misinformation. They found that inoculating messages that (1) explain the flawed argumentation technique used in the misinformation or that (2) highlight the scientific consensus on climate change were effective in neutralizing the negative influence of misinformation on perceived consensus.³⁸ Research into the effectiveness of inoculating messages is consistent with educational research suggesting that teaching approaches that directly address

misconceptions stimulate greater engagement with scientific concepts, which results in more effective and longer-lasting learning.^{38,41,42} However, one limitation of inoculating students against misinformation is that the approach must start early on in their educational journey and treatment requires a sustained intervention.² Given that students will be faced with misinformation outside a classroom environment, where inoculating messages will not be present, they need to be equipped with skills to evaluate information individually.

Digital Media and Information Literacy is a framework for equipping students and citizens with the skills to use and engage with all forms of media critically and responsibly and has been used to help students evaluate misinformation. The Stanford Education Research Group has conducted a considerable amount of research on Digital Media and Information Literacy.^{26,32,43} In particular, the group utilized professional fact-checker strategies and empirically tested this approach with students by creating online modules. Lateral reading is one fact-checker strategy they investigated, which involves leaving an unknown website to consult other sources to evaluate the original source.²⁶ They found college students significantly engaged in lateral reading in the post-test compared to the pre-test which suggests students can learn to evaluate the credibility of online sources through asynchronous instruction embedded in regular course content.²⁶ Fact-checkers also keep three questions in mind when they evaluate sources via lateral reading: (1) Who's behind the information, (2) What's the evidence? and (3) What do other sources say?³² These questions gave inspiration for the development of a Civic Online Reasoning curriculum – the ability to effectively search for, evaluate, and verify social and political information online.^{32,43} A range of short tasks were completed by 405 middle school, 348 high school and 141 college students across 12 states to assess students' civic online reasoning.⁴³ Findings show that across tasks and grade levels, students struggled to evaluate online claims, sources, and evidence, highlighting the need for materials that support students' development of civic online reasoning skills.⁴³ While these studies address some scientific issues, they are not specifically situated in a STEM context. Therefore turning to science education literature, a study established a baseline assessment of students' abilities to assess scientific information in social media.⁴⁴ Thirty-three high school students engaged in group discussions to identify (1) their experiences with social media in the science classroom, (2) their strategies for dealing with science-based information from three Instagram posts, and (3) their perception of the role of social media for informational purposes.⁴⁴ Qualitative analysis revealed students frequently use social media for information purposes and perceive social media as relevant to science education.⁴⁴ Additionally, students were successful at applying general media literacy and information technology literacy strategies but struggled with science-related strategies.⁴⁴ These findings show that students were unable

to make adequate use of their content knowledge they had learned during class when making conclusions about media messages. Therefore, educators need to give students opportunities to apply their knowledge to current, controversial, and complex media issues in science and distinguish between credible and not credible information.⁴⁵

In recent years, science education researchers have created interventions for promoting knowledge of science on modern media types.⁴⁴ For example, a study in the context of education for sustainable development examined how messages from the media manipulated high school students.⁴⁶ Different types of manipulation techniques were explicitly presented to the students allowing them to identify the techniques from media messages and assess their impact.⁴⁶ A post-test revealed that most students were able to identify and decode techniques.⁴⁶ Additionally, the use of advertisement methods in teaching did not facilitate the assimilation of knowledge related to environmental science but did improve the attitudes towards environmental-friendly and sustainable approaches.⁴⁶ In a quasi-experimental study, a six-week intervention was created on sourcing, using science-based texts on climate change and nuclear power.⁴⁷ The findings showed that students who participated in the sourcing intervention placed more value on source information when selecting texts, invested more time and effort in processing the texts they selected, and more frequently attributed textual ideas to their respective sources.⁴⁷

While studies have focused on examining educational strategies for supporting the evaluation of sources and plausibility of claims, there has been little work on supporting students in critiquing the claims for flawed scientific reasoning.^{34,48} In one recent study, high school students thought aloud with a Web media text containing erroneous claims about vaccination safety.³⁴ While some students were initially critical of the article, other students who immediately accepted the author's flawed claims as credible changed their perspective when directed to critique the article.³⁴ These findings suggested that if students are given the opportunity to critique, they may evaluate claims more thoroughly and become more critical of misinformation.³⁴ In a follow-up study, the authors investigated the gap in evaluation strategies to tackle misinformation, focusing on supporting students in the practice of critique.⁴⁸ Tseng et al (2021) tested the efficacy of a structured reading support intervention targeting the evaluation and critique of flawed scientific claims in an online setting.⁴⁸ Utilizing a pre-and post-test design, high school students were given two persuasive scientific articles and a critical reading guide for only the treatment group.⁴⁸ Students from the treatment group demonstrated increased epistemic vigilance (i.e., a process of being critically aware of cues that indicate the possibility of being misinformed by others) of misinformation, with a moderate effect size.⁴⁸ This study proposed that to reason effectively with science

misinformation in the media, it is necessary for students to evaluate claims for the quality of reasoning and to question and critique potential threats to scientific validity.⁴⁸ Reasoning with misinformation in the media has been studied by researchers in cognitive psychology;^{49,50} however, more research is needed to investigate pedagogical methods that might impact how students evaluate flawed information.⁴⁸

Critically thinking and argumentation on social scientific issues are approaches for reasoning with misinformation that have been receiving increased attention in science education based on the widespread 21st-century misinformation.⁵¹ In a recent article on misinformation featured in the University of Ottawa's Gazette, Professor Rioux-Beaulne also communicates the need for people to "take a more critical and deeper look at knowledge, with institutions playing a formative role in critical thinking".⁵² Social scientific issues are "controversial, socially relevant, real-world problems that are informed by science and often include an ethic component".⁵³ Thinking critically and practicing argumentation work must go hand-in-hand, as one's decision about a scientific claim (e.g., whether the information is true or not) is based on judgements derived from argumentation using critical thinking.⁵¹ These approaches have received more attention as scholars have argued that students need to be better prepared to assess online scientific information from a variety of sources.⁵⁴ While instruction on source evaluation is an important component for assessing information,⁴⁷ it is not sufficient.⁵⁴ Students need to learn how to evaluate the connections between sources of information and knowledge claims which requires the development of critical thinking and argumentation skills.^{51,54}

Empirical research has shown that critical thinking and argumentation practices help students to identify misinformation.⁵¹ One study engaged a small group of secondary students in online activities that required them to practice critical thinking and argumentation when asked to determine if COVID-19 headlines were true or false. The students could identify fake coronavirus headlines and critically argued why they considered them as true or false; however, very few arguments went beyond just questioning the validity of the headline to its sources and authorship.⁵¹ Most students assessed the content of the claim by using their own knowledge or empirical evidence, without asking critical questions about the source of the information.⁵¹ The authors emphasize the need to design more critical thinking activities that guide students to analyze various aspects of controversial information to prevent the spread of disinformation and misinformation.⁵¹

Systems thinking (ST) overlaps with competencies of critical thinking and argumentation as shown in the Next Generation Science Standards.⁵⁵ However, ST adds another layer as it emphasizes the interdependence of components of complex socio-scientific issues with other systems (e.g., social,

environmental) and helps to visualize the connections between these components.²⁵ Therefore, designing activities with a ST lens might help promote students' critical thinking and argumentation skills when dealing with misinformation. ST and mapping strategies have been very briefly explored in socio-scientific issues instruction, but not in the context of dis- or misinformation on these issues.^{56,57} Therefore, research is needed to explore the impact ST might have on helping students critically evaluate misinformation.

Our goals in this study are to experimentally investigate the impact of using a ST approach to support the evaluation of scientific misinformation. Specifically, we aim to investigate the impact of a ST workshop that teaches students system mapping strategies and provides them with ST prompts to help them evaluate information (e.g., a combination of accurate and flawed information from the media). The information that they evaluate will be used to create arguments about a scientific issue that is rooted in organic chemistry. We intend to gain evidence for whether a ST approach can be a strategy used in chemistry courses to help students learn to reason with scientific misinformation.

5.3 Theoretical Frameworks

This study is guided by two overarching frameworks: (1) Epistemic vigilance and (2) Scientific argumentation. Epistemic vigilance refers to one's ability to be critically aware of the validity of information to protect against misleading information. Therefore, epistemic vigilance can be attained by thinking critically, where individuals assess an author's perceived competence and trustworthiness and evaluate the accuracy of claims and supporting arguments.^{49,58} Sperber et al. (2010) define aspects of epistemic vigilance to consist of being critically aware of the validity of claims and the quality and trustworthiness of the source.⁴⁹

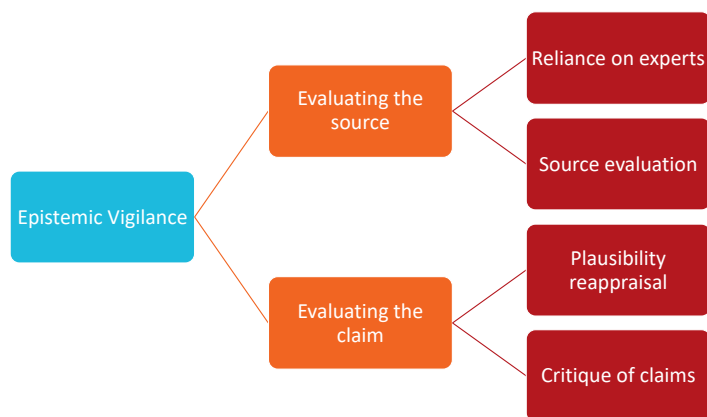


Figure 21. Strategies to support learners' development of epistemic vigilance.

This definition is supported by empirical work conducted by researchers in educational psychology, who have investigated the important components of epistemic vigilance and approaches that support learners' development of epistemic vigilance (Figure 21).⁴⁸ Methods to enhance students' awareness of source quality include reliance on experts^{59–61} and evaluating the source of the claims.^{43,47,62–66} Strategies aimed at supporting students' scrutiny of claims and validity include reassessing plausibility^{67,68} and engaging in the critique of claims.^{34,48}

Engaging in critiquing information is also a central practice for evidence-based scientific reasoning.^{55,69} Researchers have argued that reasoning with scientific information requires both constructing an understanding of scientific information and critiquing the connections between the claim and evidence that are presented.^{34,70–72} Additionally, since the evaluation of information – encompassing argumentation, critique, and analysis – plays a pivotal role in the scientific process that connects inquiry to understanding,⁶⁹ engaging in evaluation is essential for the construction of reliable knowledge.³⁴ Previous research has indicated that the tendency to critique information requires conscious activation of critical awareness.^{34,49} Therefore, in our study, we first prompt students to think critically about the validity of claims and sources by engaging students in a module on the introduction of scientific literacy. The second part of our study focuses on constructing an understanding of scientific information. We propose ST skills can be used in the practice of scientific argumentation by aiding in the construction of knowledge about a scientific topic. Therefore, we teach students ST and provide them with ST prompts to evaluate information. This information will be used to create scientific arguments on a scientific topic in the media.

Scientific argumentation is the analytical framework used in this study. Arguments have the goal of using evidence to persuade and justify a claim and using data and reasoning to advance that claim.^{73–76} Since a claim is in doubt, constructing an argument about the relation between known data and an explanation will advance the claim.^{73,74} Arguments also provide insight on how students reason about phenomena.^{77–80} Additionally, chemistry education research has investigated students' reasoning by analyzing their scientific arguments about chemical phenomena.^{73,77,81–84} Therefore, we will analyze students' arguments by using the modes of reasoning dimension of a commonly used framework in chemistry education.^{77,81,82,85} There are four modes of reasoning: descriptive, relational, linear causal, and multi-component causal.^{77,81,82,85} Descriptive arguments present evidence primarily using surface-level features without additional context.⁷³ Relational arguments discuss and connect evidence in a correlational, non-causal manner.⁷³ Causal arguments include explanations of cause-effect relationships (i.e., why). Linear causal only connects single variables to an effect while multicomponent causal

considers multiple factors in the evidence and their combined impact on outcomes.⁷³ This framework is used as it aligns with the intended learning outcomes of the course where we intend to implement this study.⁶⁹

5.4 Research Questions and Hypotheses

Herein, we describe our analysis plan to investigate students' scientific arguments for a writing assignment designed to elicit causal arguments when evaluating multiple sources on a scientific topic. We are primarily interested in determining if ST can help students reason in generating scientific arguments. However, we also want to determine what aspects of ST students use in their arguments and what they find beneficial and challenging when using a ST approach to inform teaching approaches if evidence shows ST is an effective approach. Therefore, this study is guided by the following research questions:

RQ1: What effect does a ST workshop have on organic chemistry students' modes of reasoning in scientific arguments when evaluating misinformation?

RQ2: When given systems thinking prompts, what aspects of systems thinking do organic chemistry students use to generate scientific arguments to evaluate misinformation?

RQ3: What are the benefits and challenges of using a ST approach for developing scientific arguments?

Investigating **RQ1** will tell us if ST can and should be used as an approach for creating scientific arguments to evaluate misinformation in chemistry education. If students can evaluate misinformation using a ST approach, there may be implications for the adaptability of this approach to multiple chemistry courses. We hypothesize that students who engage in a ST workshop will be able to analyze multiple factors of the information and see the causal connections between factors more explicitly than those who do not engage in the ST workshop. Being able to visualize many connections might also help them to weigh the different pieces of evidence (e.g., scientifically accurate versus flawed information). Therefore, before engaging in the workshop we predict students will use more descriptive and relational modes of reasoning, as our previous study has shown students tend to use these types of reasoning more frequently when not explicitly prompted to do so.⁸⁶ After a ST workshop where students are taught ST and provided with ST prompts, students might present more causal modes of reasoning in their arguments. Additionally, previous research in science communication indicates that it is difficult to change people's view of scientific information once their perspectives have been shaped.^{39,48,87}

Therefore, we predict that students who report more neutral beliefs about science will experience a larger improvement in their reasoning after completing the workshop.

Investigating **RQ2** will contribute to research on students' ST skills in chemistry education. Implications from our previous study in Chapter 3 will guide the development of prompts used to elicit ST skills. In this study, we will identify students' ability to demonstrate ST skills when provided with prompts and instructions on how to demonstrate certain ST skills. Additionally, investigating RQ2 will tell us what ST skills students use when evaluating information, which will help us understand how ST might be used as a teaching strategy to scaffold the evaluation of online scientific information.

Investigating **RQ3** is needed as more research is required to understand students' perspectives and attitudes toward a ST approach. Research has already indicated secondary school students like to see social media context implemented appropriately in science lessons. However, when evaluating misinformation, the literature does not communicate what students find beneficial and/or challenging. Investigating students' perspectives and attitudes toward a ST approach when evaluating misinformation may help us understand what aspects of ST are beneficial and not beneficial for constructing a scientific argument to a misinformation prompt. This data can inform researchers and educators on how a ST approach might or might not be used for evaluating misinformation.

5.5 Methods

5.5.1 Context and Participants

Very few resources have been published on integrating ST into an organic chemistry course. Therefore, when choosing a scientific topic to use for this study, we needed to consider the relevance of organic chemistry behind the topic and the prevalence of misinformation about the topic in the media. We chose aspartame as the chemical of interest used in this study as this chemical has been commonly misinformed in the media, has connections to organic chemistry II content (e.g., Fischer Esterification, Condensation), and is a common ingredient in many food products which applies to all students. Aspartame is a low-calorie artificial sweetener, sold under brand names such as NutraSweet and Equal, that has been in use worldwide since the early 1980s.⁸⁸ Aspartame is used in many foods and beverages because it is much sweeter than sugar, so much less of it can be used to give the same level of sweetness.⁸⁹ However, there has been controversy about the safety of consuming aspartame including a multitude of claims with varying levels of scientific certainty linking aspartame to adverse health outcomes (e.g., cancer, kidney disease, seizures, headaches, Alzheimer's disease).^{88,90,91} Aspartame has not been conclusively linked to any serious side effects or health problems, but certain people with

Phenylketonuria should avoid aspartame.⁹² The US Food and Drug Administration, European Food and Safety Authority, and Health Canada have all reviewed aspartame and found it to be safe for human consumption and allow its use in various foods.^{89,92–95} However, recently the International Agency for Research on Cancer, the World Health Organization and the Food and Agriculture Organization classified aspartame as possibly carcinogenic to humans indicating “limited evidence” for this claim.⁹⁶ Health Canada has indicated they will review the summary assessments and full reports by the World Health Organization’s International Agency for Research on Cancer once they are released.⁹⁴

We aim to recruit undergraduate chemistry students taking Organic Chemistry II at the University of Ottawa. Organic Chemistry II is offered in the summer and fall semesters after students take Organic Chemistry I in the winter semester of their first year. The primary investigator of this research teaches one section of the Organic Chemistry II course in the fall semester; therefore, we have access to organic chemistry II students (approximately 400 students enrolled) for this study. Given that this research will be embedded as part of a course, and will align with course learning outcomes, participants’ compensation for completing the activities in the study will be a small percentage of their course grade (e.g., 1 or 2% or bonus). The University of Ottawa teaches organic chemistry using the Patterns of Mechanisms curriculum where the electron-pushing formalism is taught before concepts of reactivity.⁹⁴ The formation of aspartame involves the Fischer Esterification reaction and condensation reaction; therefore, based on the organic chemistry curriculum, these reactions are taught in the Organic Chemistry II course (Figure 22).

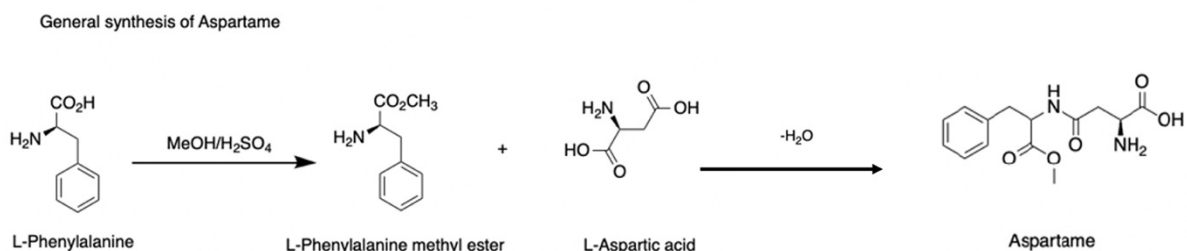


Figure 22. General synthesis of aspartame.

L-phenylalanine reacts with methanol in the presence of an acid catalyst to create L-phenylalanine methyl ester. This ester further reacts with L-aspartic acid in a condensation reaction to form aspartame. When ingested in the body, aspartame breaks down into 50% L-phenylalanine, 10% methanol, and 40% L-aspartic acid. Methanol can be oxidized in the liver to form formaldehyde and further oxidized to form formate. The synthesis and metabolism of aspartame are important reactions

for comprehending how misinformation of aspartame is formed. Students will be able to use their knowledge learned from the course to propose the synthesis of aspartame.

5.5.2 Instrument and procedure for data collection

We created an experimental design to investigate the effects of a ST workshop on students' reasoning in scientific arguments, identify the ST skills used by Organic Chemistry II students to generate scientific arguments, and collect student perspectives and attitudes when using a ST approach to evaluate misinformation.⁹⁸ The experimental study consists of several parts: (1) recruiting participants, (2) collection of participants' prior knowledge and beliefs on science and safety of aspartame, (3) an introduction to science literacy module, (4) pre-test, (5) a workshop on evaluating information from web sources, (6) post-test, and (7) participant group feedback (Figure 23). Parts 1 to 4 of the study will be conducted online and asynchronously, and Parts 5 to 7 will be conducted in person and synchronously given the time constraints in a course. We will apply to the University of Ottawa's Research Ethics Board to approve all parts of this study prior to implementation.

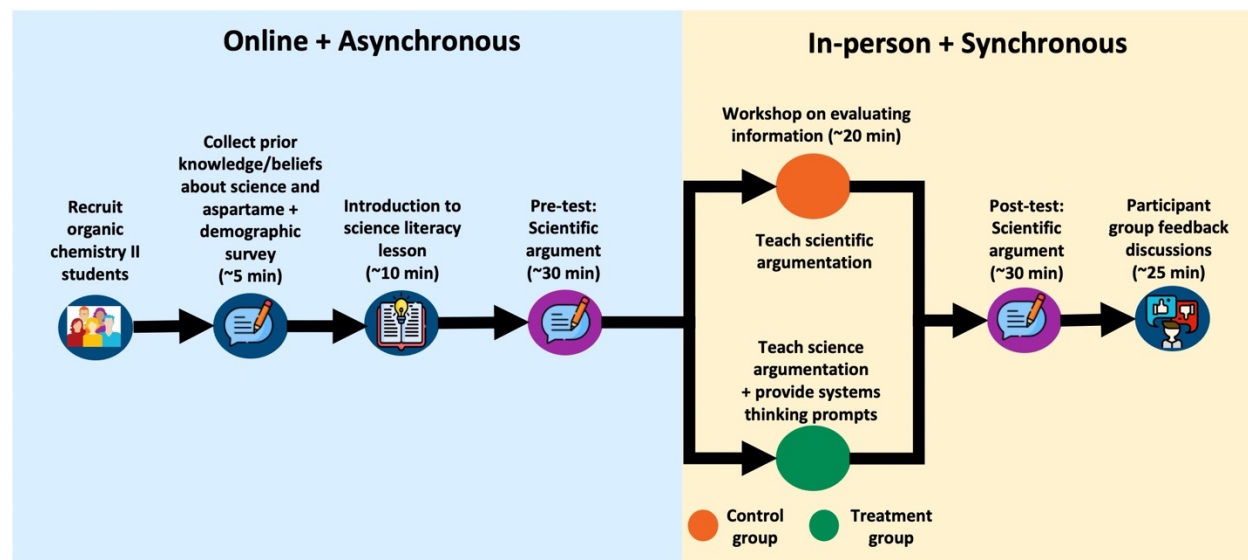


Figure 23. Design of a quasi-experimental study.

All Organic Chemistry II students enrolled in the course will automatically be enrolled in the study unless they choose to opt-out (Part 1) by completing a Google form. The course professor will place information about the study in the course syllabus and in the class online announcements.

Students will complete Parts 1 to 4 asynchronously on an online assignment provided on the course website. Part 2 will involve a questionnaire to collect students' prior knowledge and beliefs about science and the topic of aspartame as well as a demographic survey (approximately 5 minutes). This

questionnaire is included in this study as participants' pre-existing knowledge and attitudes towards science and the misinformation topic as well as their sociodemographic background may influence how they interact with the activities in their assigned condition (i.e., treatment or control).⁴⁸ Additionally, motivation has been shown to influence how readers evaluate persuasive text.⁹⁹ The questionnaire and demographic survey will be developed and then reviewed by experts in the field to collect evidence for content validity. Part 3 will provide participants with a short online module to introduce science literacy as previous research has identified evaluating information needs to involve evaluation of the sources and evaluation of the claims.^{48,49,100–102} For example, asking relevant questions about the author's intentions, identifying biases, and evaluating the quality and volume of sources used as evidence. This module is intended to cue participants' epistemic vigilance (see theoretical framework section) before the experimental phase of the study to control for this factor. One resource that can be used in the development of the module is Chapter 2, Science and the Sky, in *Environmental Science for Changing World*.¹⁰⁰ This chapter discusses the kinds of questions that are under the purview of science, how scientific hypotheses are generated and tested, the differences in the types of scientific studies, and provides an overview of the process of science.¹⁰³

The pre-and post-test will be made identical to measure the effect of a workshop on participants' scientific arguments on aspartame (each approximately 30 minutes to complete). The tests will consist of a writing assignment where participants will first be provided with a brief background on the use of aspartame and a variety of sources (e.g., websites and scientific articles). Some of these sources will contain flawed scientific claims about aspartame. Then, participants will be assigned the task of writing an argument about the future use of aspartame while consulting these sources and potentially exploring other sources. Specifically, they will be asked to construct an argument on the online assignment for the following question: Do you think aspartame should continue to be used for human consumption or be banned by government agencies? Explain why.

A workshop on evaluating information will be provided in two sections of weekly tutorials offered as part of the Organic Chemistry II course at the University of Ottawa (approximately 20 minutes). Using two sections of the weekly tutorials provides a good opportunity for creating control and treatment groups for the study and does not impede directly on course theory time. Students will be randomly assigned to a treatment and control group. The workshops will occur in-person and synchronously during the scheduled tutorials along with the remaining parts of the study. The control group (n = 200) will be taught scientific argumentation to help participants evaluate information on aspartame and will proceed with completing the post-test individually. The treatment group (n = 200)

will be taught scientific argumentation and system mapping and will be guided through systems thinking prompts when evaluating information on aspartame. For example, participants might be asked to (1) identify multiple contexts where aspartame might impact or is impacted by (e.g., human health, food availability and prices, environmental health) (2) what are the benefits and consequences of aspartame in these contexts, (3) what is the chemical reaction for the production and decomposition/metabolism of aspartame and how do these chemical components relate to the contexts, and (4) what are the effects when the chemical components increase or decrease over time?. Participants will be asked to consider using these prompts when constructing their scientific argument in the post-test, completed individually. When working through the ST prompts, participants will construct system maps using the online tool, SOCKit, to help them visualize concepts and connections.¹⁰⁴ Participants' scientific arguments in the post-test will be recorded on another online assignment provided on the course website. After the post-test, participants will be asked to discuss the activity in small groups (e.g., 3 or 4 participants) by answering some guided questions. One member of the group will be tasked with writing down discussion points for each question on the online activity.

5.5.3 Planned data analyses

The data collected from this study will be analyzed qualitatively and quantitatively according to the research questions. RQ1 will be investigated by first analyzing students' scientific arguments by their modes of reasoning.^{77,81} After identifying the concepts students discussed and the nature of connections between those concepts, students' scientific arguments will be defined by the modes of reasoning: descriptive, relational, linear causal, and multicomponent causal.⁷⁷ Additionally, we will analyze the extent participants' scientific arguments include accurate versus flawed scientific information in their argument. We will establish inter-rater reliability by a second researcher analyzing a subset of students' responses. Then, statistical analyses will be done using SPSS, to investigate the differences between the pre-test and post-test scores for the treatment and control groups. Specifically, the respective percentages of (1) causal (e.g., linear and multicomponent) and non-causal (descriptive and relational) arguments and (2) accurate versus inaccurate arguments will be compared to determine the extent to which students' arguments differed between and within the treatment and control groups. Additional statistical tests between treatment and control groups will be conducted to determine the effect of other mediated variables on scientific arguments such as participants' beliefs about science and aspartame and other demographics (e.g., gender, race). RQ2 will be investigated by analyzing participants' scientific arguments using qualitative coding approaches, followed by analyzing for themes.⁹⁸ Specifically, we will

use our ST rubric from our previous study to identify what ST skills students demonstrate when constructing their scientific arguments.⁸⁶ Lastly, RQ3 will be investigated by analyzing participants' open-ended responses through qualitative coding approaches that will capture themes within the data.⁹⁸ We will conduct a set of interviews with a subset of participants to increase the validity of the results (n = 20).^{105–107}

5.6 Next Steps

The next steps for this project will be to (1) develop instruments and materials that will be used in the study, (2) submit an ethics application to the Office of Research Ethics and Integrity at the University of Ottawa, and (3) complete a pilot study with students who have taken Organic Chemistry II (n = 5). A pilot study will help identify whether the instruments in the study produce data that align with the intended goals and provides the opportunity to make changes if misalignment is shown. The instruments that will need to be developed are (1) a questionnaire for collecting students' prior knowledge and beliefs on science and aspartame, (2) demographic survey, (3) pre-/post-test, and (4) group feedback questionnaire. We can use existing prior knowledge and belief questionnaires from the literature as a guide to create questions specific to our study.^{48,51} We have previously created demographic surveys in our previous ST studies that we can draw questions from for this study.^{86,108} Lastly, the background information for aspartame for the pre-/post-test writing assignment needs to be strategically created to include enough information to introduce aspartame without persuading students to one side of the argument. A list of approximately six sources also needs to be selected and included in the instructions for the writing assignment. Half of the resources will contain misinformation, and the other half will include accurate scientific information about aspartame. Lastly, a group feedback questionnaire containing open-ended questions (approximately 5) will need to be created to identify aspects of the writing assignment activity students found beneficial and challenging.

Other materials that need to be developed are the (1) science literacy online lesson and (2) workshop plan and resources for the treatment and control groups. We can draw upon existing resources in the literature to help build these materials.^{103,109,110}

Once all the instruments and materials are developed, an ethics application can be created and submitted. In the process of waiting for ethics approval, the study can be piloted informally with organic chemistry II students (n = 5) to identify issues such as the timing required to complete certain tasks and time to complete the entire study and whether the questions and prompts that are asked to elicit the data we intend to collect (e.g., response-process validity).

Additionally, completion of these next steps will need an appropriate timeline that accounts for when the Organic Chemistry II course is offered.

5.7 Conclusion

Our world is faced with many global crises and among the most pressing challenges, misinformation and disinformation has emerged as the top risk over the next two years.¹ Education plays a critical role in helping equip citizens and scientists with the knowledge and skills required to identify and evaluate false information. There have been calls for science education to address this need.^{2–4}

In a draft commentary in section 5.2.1, we propose using a ST approach to help evaluate information, as ST involves a holistic perspective. No research has explored the impact of a ST approach for evaluating false science information. Therefore, we make a call to action for investigating ST's role in evaluating misinformation.

Contributing to this need of educational research, we designed an experimental study that investigates the effects of a ST workshop on students' reasoning in scientific arguments, identifies the ST skills used by Organic Chemistry II students to generate scientific arguments, and collects student perspectives and attitudes when using a ST approach to evaluate misinformation.⁹⁸

During the duration of my degree, I did not have time to conduct the experimental study; therefore, I leave the reader with planned data analyses and next steps required to complete this project.

5.8 References

- (1) McLennan, M.; Zurich Insurance Group. *The Global Risks Report 19th Edition*; World Economic Forum: Geneva, Switzerland, 2024.
- (2) Osborne, J. F.; Pimentel, D.; Alberts, B.; Allchin, D.; Barzilai, S.; Bergstrom, C.; Coffey, J.; Donovan, B.; Dorph, R.; Kivinen, K.; Kozyreva, A.; Perkins, K.; Perlmutter, S.; Wineburg, S. *Science Education in an Age of Misinformation*; Stanford University, 2022.
- (3) Allchin, D.; Bergstrom, C. T.; Osborne, J. Transforming Science Education in an Age of Misinformation. *J. Coll. Sci. Teach.* **2024**, *53* (1), 40–43.
<https://doi.org/10.1080/0047231X.2023.2292409>.
- (4) Howell, E. L.; Brossard, D. (Mis)Informed about What? What It Means to Be a Science-Literate Citizen in a Digital World. *Proc. Natl. Acad. Sci.* **2021**, *118* (15), e1912436117.
<https://doi.org/10.1073/pnas.1912436117>.
- (5) Agle, J. Assessing Changes in US Public Trust in Science amid the COVID-19 Pandemic. *Public Health* **2020**, *183*, 122–125. <https://doi.org/10.1016/j.puhe.2020.05.004>.

- (6) Agley, J.; Xiao, Y. Misinformation about COVID-19: Evidence for Differential Latent Profiles and a Strong Association with Trust in Science. *BMC Public Health* **2021**, *21* (1), 89. <https://doi.org/10.1186/s12889-020-10103-x>.
- (7) Nicolo, M.; Kawaguchi, E.; Ghanem-Uzqueda, A.; Soto, D.; Deva, S.; Shanker, K.; Lee, R.; Gilliland, F.; Klausner, J. D.; Baezconde-Garbanati, L.; Kovacs, A.; Van Orman, S.; Hu, H.; Unger, J. B. Trust in Science and Scientists among University Students, Staff, and Faculty of a Large, Diverse University in Los Angeles during the COVID-19 Pandemic, the Trojan Pandemic Response Initiative. *BMC Public Health* **2023**, *23* (1), 601. <https://doi.org/10.1186/s12889-023-15533-x>.
- (8) Brown School of Public Health. *New Analysis Shows Vaccines Could Have Prevented 318,000 Deaths*. Global Epidemics. <https://globalepidemics.org/2022/05/13/new-analysis-shows-vaccines-could-have-prevented-318000-deaths/>.
- (9) Hopf, H.; Krief, A.; Mehta, G.; Matlin, S. A. Fake Science and the Knowledge Crisis: Ignorance Can Be Fatal. *R. Soc. Open Sci.* **2019**, *6* (5), 190161. <https://doi.org/10.1098/rsos.190161>.
- (10) Babii, A.-N. The Use of Critical Thinking Against Fake News. In *NORDSCI Conference proceedings, Book 1 Volume 3*; SAIMA Consult Ltd, 2020. <https://doi.org/10.32008/NORDSCI2020/B1/V3/14>.
- (11) Otte, L.; Beeken, M. "COVID-19 between Myth and Science"—Innovative Experiments for Analyzing Fake News Inside and Outside the Chemistry Classroom. *J. Chem. Educ.* **2022**, *99* (5), 1890–1899. <https://doi.org/10.1021/acs.jchemed.1c01262>.
- (12) Ha, L.; Andreu Perez, L.; Ray, R. Mapping Recent Development in Scholarship on Fake News and Misinformation, 2008 to 2017: Disciplinary Contribution, Topics, and Impact. *Am. Behav. Sci.* **2021**, *65* (2), 290–315. <https://doi.org/10.1177/0002764219869402>.
- (13) Erduran, S. AI Is Transforming How Science Is Done. Science Education Must Reflect This Change. *Science* **2023**, *382* (6677), eadm9788. <https://doi.org/10.1126/science.adm9788>.
- (14) Sotério, C.; Queiroz, S. L. Chemistry Students as Science Journalists: Creating a Virtual Magazine about COVID-19. *J. Chem. Educ.* **2022**, acs.jchemed.2c00277. <https://doi.org/10.1021/acs.jchemed.2c00277>.
- (15) World Health Organization. *An Ad Hoc WHO Technical Consultation Managing the COVID-19 Infodemic: Call for Action*; World Health Organization: Geneva, 2020; p 43. <https://www.who.int/publications/i/item/9789240010314> (accessed 2022-12-21).
- (16) *United Nations' Sustainable Development Goals*. <http://sustainabledevelopment.un.org/> (accessed 2022-12-16).

- (17) Lazer, D. M. J.; Baum, M. A.; Benkler, Y.; Berinsky, A. J.; Greenhill, K. M.; Menczer, F.; Metzger, M. J.; Nyhan, B.; Pennycook, G.; Rothschild, D.; Schudson, M.; Sloman, S. A.; Sunstein, C. R.; Thorson, E. A.; Watts, D. J.; Zittrain, J. L. The Science of Fake News. *Science* **2018**, 359 (6380), 1094–1096. <https://doi.org/10.1126/science.aao2998>.
- (18) NDTV News Service. WhatsApp Selects 20 Teams To Curb Fake News Globally, Including In India; 2018. <https://www.ndtv.com/india-news/whatsapp-selects-20-teams-to-curb-fake-news-globally-including-in-india-1946482> (accessed 2022-08-11).
- (19) Scheufele, D. A.; Krause, N. M. Science Audiences, Misinformation, and Fake News. *Proc. Natl. Acad. Sci.* **2019**, 116 (16), 7662–7669. <https://doi.org/10.1073/pnas.1805871115>.
- (20) Brossard, D.; Scheufele, D. A. The Chronic Growing Pains of Communicating Science Online. *Science* **2022**, 375 (6581), 613–614. <https://doi.org/10.1126/science.abo0668>.
- (21) Fryling-Indiana, K. Scientists Call for Action in Fight against “Fake News.” *Futurity*; 2018.
- (22) Nugent, J. *Advance technology literacy and bring learners’ 21st-century skills up to code with the Hour of Code!* National Science Teaching Association. <https://www.nsta.org/advance-technology-literacy-and-bring-learners-21st-century-skills-code-hour-code> (accessed 2022-12-21).
- (23) Zimmerman, J. B.; Anastas, P. T.; Erythropel, H. C.; Leitner, W. Designing for a Green Chemistry Future. *Science* **2020**, 367 (6476), 397–400. <https://doi.org/10.1126/science.aay3060>.
- (24) Selin, N. E. Lessons from a Pandemic for Systems-Oriented Sustainability Research. *Sci. Adv.* **2021**, 7 (22), eabd8988. <https://doi.org/10.1126/sciadv.abd8988>.
- (25) 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>.
- (26) Breakstone, J.; Smith, M.; Connors, P.; Ortega, T.; Kerr, D.; Wineburg, S. Lateral Reading: College Students Learn to Critically Evaluate Internet Sources in an Online Course. *Harv. Kennedy Sch. Misinformation Rev.* **2021**, 2 (1), 1–17. <https://doi.org/10.37016/mr-2020-56>.
- (27) 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**, 99 (7), 2474–2483. <https://doi.org/10.1021/acs.jchemed.2c00138>.
- (28) Selin, H.; Selin, N. E. The Human–Technical–Environmental Systems Framework for Sustainability Analysis. *Sustain. Sci.* **2023**, 18 (2), 791–808. <https://doi.org/10.1007/s11625-022-01177-0>.
- (29) Bennett, S.; Maton, K.; Kervin, L. The ‘Digital Natives’ Debate: A Critical Review of the Evidence. *Br. J. Educ. Technol.* **2008**, 39 (5), 775–786. <https://doi.org/10.1111/j.1467-8535.2007.00793.x>.

- (30) Palfrey, J.; Gasser, U. *Born Digital: Understanding the First Generation of Digital Natives*, New York, Basic Books, 2008, pp. 20–24.
- (31) Hargittai, E. Digital Na(t)ives? Variation in Internet Skills and Uses among Members of the “Next Generation.” *Sociol. Inq.* **2010**, *80* (1), 92–113. <https://doi.org/10.1111/j.1475-682X.2009.00317.x>.
- (32) Breakstone, J.; Smith, M.; Wineburg, S.; Rapaport, A.; Carle, J.; Garland, M.; Saavedra, A. Students’ Civic Online Reasoning: A National Portrait. *Educ. Res.* **2021**, *50* (8), 505–515.
- (33) Cheng, C.; Bråten, I.; Yang, F.; Brandmo, C. Investigating Structural Relationships among Upper-Secondary School Students’ Beliefs about Knowledge, Justification for Knowing, and Internet-Specific Justification in the Domain of Science. *J. Res. Sci. Teach.* **2021**, *58* (7), 980–1009. <https://doi.org/10.1002/tea.21689>.
- (34) Tseng, A. S. Students and Evaluation of Web-Based Misinformation about Vaccination: Critical Reading or Passive Acceptance of Claims? *Int. J. Sci. Educ. Part B* **2018**, *8* (3), 250–265. <https://doi.org/10.1080/21548455.2018.1479800>.
- (35) Norris, S. P.; Phillips, L. M. Interpreting Pragmatic Meaning When Reading Popular Reports of Science. *J. Res. Sci. Teach.* **1994**, *31* (9), 947–967. <https://doi.org/10.1002/tea.3660310909>.
- (36) Ratcliffe, M. Evaluation of Abilities in Interpreting Media Reports of Scientific Research. *Int. J. Sci. Educ.* **1999**, *21* (10), 1085–1099. <https://doi.org/10.1080/095006999290200>.
- (37) Cook, J. Countering Climate Science Denial and Communicating Scientific Consensus. In *Oxford Research Encyclopedia of Climate Science*; Oxford University Press, 2016. <https://doi.org/10.1093/acrefore/9780190228620.013.314>.
- (38) Cook, J.; Lewandowsky, S.; Ecker, U. K. H. Neutralizing Misinformation through Inoculation: Exposing Misleading Argumentation Techniques Reduces Their Influence. *PLOS ONE* **2017**, *12* (5), e0175799. <https://doi.org/10.1371/journal.pone.0175799>.
- (39) Lewandowsky, S.; Ecker, U. K. H.; Seifert, C. M.; Schwarz, N.; Cook, J. Misinformation and Its Correction: Continued Influence and Successful Debiasing. *Psychol. Sci. Public Interest* **2012**, *13* (3), 106–131. <https://doi.org/10.1177/1529100612451018>.
- (40) McGuire, W. J.; Papageorgis, D. The Relative Efficacy of Various Types of Prior Belief-Defense in Producing Immunity against Persuasion. *J. Abnorm. Soc. Psychol.* **1961**, *62* (2), 327–337. <https://doi.org/10.1037/h0042026>.

- (41) Ecker, U. K. H.; Hogan, J. L.; Lewandowsky, S. Reminders and Repetition of Misinformation: Helping or Hindering Its Retraction? *J. Appl. Res. Mem. Cogn.* **2017**, *6* (2), 185–192. <https://doi.org/10.1037/h0101809>.
- (42) Kowalski, P.; Taylor, A. K. The Effect of Refuting Misconceptions in the Introductory Psychology Class. *Teach. Psychol.* **2009**, *36* (3), 153–159. <https://doi.org/10.1080/00986280902959986>.
- (43) McGrew, S.; Breakstone, J.; Ortega, T.; Smith, M.; Wineburg, S. Can Students Evaluate Online Sources? Learning From Assessments of Civic Online Reasoning. *Theory Res. Soc. Educ.* **2018**, *46* (2), 165–193. <https://doi.org/10.1080/00933104.2017.1416320>.
- (44) Belova, N.; Krause, M.; Siemens, C. Students' Strategies When Dealing with Science-Based Information in Social Media—A Group Discussion Study. *Educ. Sci.* **2022**, *12* (9), 603. <https://doi.org/10.3390/educsci12090603>.
- (45) Acerbi, A.; Altay, S.; Mercier, H. *Research note: Fighting misinformation or fighting for information?*. Harvard Kennedy School Misinformation Review. <https://misinforeview.hks.harvard.edu/article/research-note-fighting-misinformation-or-fighting-for-information/>.
- (46) Kotsalas, I. P.; Antoniou, A.; Scoullou, M. Decoding Mass Media Techniques and Education for Sustainable Development. *J. Educ. Sustain. Dev.* **2017**, *11* (2), 102–122. <https://doi.org/10.1177/0973408218761229>.
- (47) Bråten, I.; Brante, E. W.; Strømsø, H. I. Teaching Sourcing in Upper Secondary School: A Comprehensive Sourcing Intervention With Follow-Up Data. *Read. Res. Q.* **2019**, *54* (4), 481–505. <https://doi.org/10.1002/rrq.253>.
- (48) Tseng, A. S.; Bonilla, S.; MacPherson, A. Fighting “Bad Science” in the Information Age: The Effects of an Intervention to Stimulate Evaluation and Critique of False Scientific Claims. *J. Res. Sci. Teach.* **2021**, *58* (8), 1152–1178. <https://doi.org/10.1002/tea.21696>.
- (49) Sperber, D.; Clément, F.; Heintz, C.; Mascaro, O.; Mercier, H.; Origgi, G.; Wilson, D. Epistemic Vigilance. *Mind Lang.* **2010**, *25* (4), 359–393. <https://doi.org/10.1111/j.1468-0017.2010.01394.x>.
- (50) Halpern, D. F. *Thought and Knowledge*, 0 ed.; Psychology Press, 2013. <https://doi.org/10.4324/9781315885278>.
- (51) Puig, B.; Blanco-Anaya, P.; Pérez-Maceira, J. J. “Fake News” or Real Science? Critical Thinking to Assess Information on COVID-19. *Front. Educ.* **2021**, *6*, 646909. <https://doi.org/10.3389/feduc.2021.646909>.

- (52) University of Ottawa Gazette. *Fighting misinformation and disinformation in society: on the agenda at the ACFAS Conference*. <https://www.uottawa.ca/research-innovation/news-all/fighting-misinformation-disinformation-society-acfas-conference> (accessed 2024-08-06).
- (53) Sadler, T. D.; Barab, S. A.; Scott, B. What Do Students Gain by Engaging in Socioscientific Inquiry? *Res. Sci. Educ.* **2007**, *37* (4), 371–391. <https://doi.org/10.1007/s11165-006-9030-9>.
- (54) Sinatra, G. M.; Lombardi, D. Evaluating Sources of Scientific Evidence and Claims in the Post-Truth Era May Require Reappraising Plausibility Judgments. *Educ. Psychol.* **2020**, *55* (3), 120–131. <https://doi.org/10.1080/00461520.2020.1730181>.
- (55) National Research Council. *Next Generation Science Standards: For States, By States*; National Academies Press: Washington, D.C., 2013; p 18290. <https://doi.org/10.17226/18290>.
- (56) Ewing, M.; Sadler, T. D. Socio-Scientific Issues Instruction. *The Science Teacher*. **2021**, *99* (2), 18–21. <https://doi.org/10.1080/00368555.2020.12293566>.
- (57) Kirk, E. A.; Sadler, T. D.; Xu, Z.; Elsner, J. N.; Lesnefsky, R. R.; Ke, L.; Zangori, L. Socioscientific Modeling: Helping Students See Systems and Understand Messy Issues. *Sci. Scope* **2024**, *47* (2), 12–17. <https://doi.org/10.1080/08872376.2024.2314698>.
- (58) Kahneman, D. *Thinking, Fast and Slow*; Thinking, fast and slow.; Farrar, Straus, and Giroux: New York, NY, US, 2011; p 499.
- (59) Baram-Tsabari, A.; Osborne, J. Bridging Science Education and Science Communication Research. *J. Res. Sci. Teach.* **2015**, *52* (2), 135–144. <https://doi.org/10.1002/tea.21202>.
- (60) Sharon, A. J.; Baram-Tsabari, A. Can Science Literacy Help Individuals Identify Misinformation in Everyday Life? *Sci. Educ.* **2020**, *104* (5), 873–894. <https://doi.org/10.1002/sce.21581>.
- (61) Feinstein, N. Salvaging Science Literacy. *Sci. Educ.* **2011**, *95*, 168–185. <https://doi.org/10.1002/sce.20414>.
- (62) Wineberg, S.; McGrew, S.; Breakstone, J.; Ortega, T. *Evaluating Information: The Cornerstone of Civic Online Reasoning*; 2016. <http://purl.stanford.edu/fv751yt5934> (accessed 2022-12-21).
- (63) Braasch, J. L. G.; Bråten, I. The Discrepancy-Induced Source Comprehension (D-ISC) Model: Basic Assumptions and Preliminary Evidence. *Educ. Psychol.* **2017**, *52* (3), 167–181. <https://doi.org/10.1080/00461520.2017.1323219>.
- (64) Bråten, I.; Stadtler, M.; Salmerón, L. The Role of Sourcing in Discourse Comprehension. In *The Routledge Handbook of Discourse Processes*; Schober, M. F., Rapp, D. N., Britt, M. A., Eds.; Routledge, 2017; pp 141–166. <https://doi.org/10.4324/9781315687384-10>.

- (65) Stadtler, M.; Bromme, R. The Content–Source Integration Model: A Taxonomic Description of How Readers Comprehend Conflicting Scientific Information. In *Processing Inaccurate Information: Theoretical and Applied Perspectives from Cognitive Science and the Educational Sciences*; Rapp, D. N., Braasch, J. L. G., Eds.; The MIT Press, 2014; p 0.
<https://doi.org/10.7551/mitpress/9737.003.0023>.
- (66) Stadtler, M.; Scharrer, L.; Macedo-Rouet, M.; Rouet, J.-F.; Bromme, R. Improving Vocational Students' Consideration of Source Information When Deciding about Science Controversies. *Read. Writ.* **2016**, *29* (4), 705–729. <https://doi.org/10.1007/s11145-016-9623-2>.
- (67) Lombardi, D.; Sinatra, G. M.; Nussbaum, E. M. Plausibility Reappraisals and Shifts in Middle School Students' Climate Change Conceptions. *Learn. Instr.* **2013**, *27*, 50–62.
<https://doi.org/10.1016/j.learninstruc.2013.03.001>.
- (68) Lombardi, D.; Bailey, J. M.; Bickel, E. S.; Burrell, S. Scaffolding Scientific Thinking: Students' Evaluations and Judgments during Earth Science Knowledge Construction. *Contemp. Educ. Psychol.* **2018**, *54*, 184–198. <https://doi.org/10.1016/j.cedpsych.2018.06.008>.
- (69) *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; National Academies Press: Washington, D.C., 2012; p 13165. <https://doi.org/10.17226/13165>.
- (70) Ford, M. Disciplinary Authority and Accountability in Scientific Practice and Learning. *Sci. Educ.* **2008**, *92* (3), 404–423. <https://doi.org/10.1002/sce.20263>.
- (71) Henderson, J. B.; MacPherson, A.; Osborne, J.; Wild, A. Beyond Construction: Five Arguments for the Role and Value of Critique in Learning Science. *Int. J. Sci. Educ.* **2015**, *37* (10), 1668–1697.
<https://doi.org/10.1080/09500693.2015.1043598>.
- (72) Osborne, J. Teaching Scientific Practices: Meeting the Challenge of Change. *J. Sci. Teach. Educ.* **2014**, *25* (2), 177–196. <https://doi.org/10.1007/s10972-014-9384-1>.
- (73) 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>.
- (74) Osborne, J. F.; Patterson, A. Scientific Argument and Explanation: A Necessary Distinction? *Sci. Educ.* **2011**, *95* (4), 627–638. <https://doi.org/10.1002/sce.20438>.
- (75) Toulmin, S. E. *The Uses of Argument*, 2nd ed.; Cambridge University Press: Cambridge, 2003.
<https://doi.org/10.1017/CBO9780511840005>.

- (76) Becker, N.; Rasmussen, C.; Sweeney, G.; Wawro, M.; Towns, M.; Cole, R. Reasoning Using Particulate Nature of Matter: An Example of a Sociochemical Norm in a University-Level Physical Chemistry Class. *Chem Educ Res Pr.* **2013**, *14* (1), 81–94. <https://doi.org/10.1039/C2RP20085F>.
- (77) 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>.
- (78) Emig, J. Writing as a Mode of Learning. *Coll. Compos. Commun.* **1977**, *28* (2), 122–128. <https://doi.org/10.2307/356095>.
- (79) Berland, L. K.; Reiser, B. J. Making Sense of Argumentation and Explanation. *Sci. Educ.* **2009**, *93* (1), 26–55. <https://doi.org/10.1002/sce.20286>.
- (80) Grimberg, B. I.; Hand, B. Cognitive Pathways: Analysis of Students' Written Texts for Science Understanding. *Int. J. Sci. Educ.* **2009**, *31* (4), 503–521. <https://doi.org/10.1080/09500690701704805>.
- (81) Sevian, H.; Talanquer, V. Rethinking Chemistry: A Learning Progression on Chemical Thinking. *Chem Educ Res Pr.* **2014**, *15* (1), 10–23. <https://doi.org/10.1039/C3RP00111C>.
- (82) Weinrich, M. L.; Talanquer, V. Mapping Students' Modes of Reasoning When Thinking about Chemical Reactions Used to Make a Desired Product. *Chem. Educ. Res. Pract.* **2016**, *17* (2), 394–406. <https://doi.org/10.1039/C5RP00208G>.
- (83) Moon, A.; Moeller, R.; Gere, A. R.; Shultz, G. V. Application and Testing of a Framework for Characterizing the Quality of Scientific Reasoning in Chemistry Students' Writing on Ocean Acidification. *Chem. Educ. Res. Pract.* **2019**, *20* (3), 484–494. <https://doi.org/10.1039/C9RP00005D>.
- (84) Moreira, P.; Marzabal, A.; Talanquer, V. Using a Mechanistic Framework to Characterise Chemistry Students' Reasoning in Written Explanations. *Chem. Educ. Res. Pract.* **2019**, *20* (1), 120–131. <https://doi.org/10.1039/C8RP00159F>.
- (85) Caspari, I.; Weinrich, M. L.; Sevian, H.; Graulich, N. This Mechanistic Step Is “*Productive*”: Organic Chemistry Students' Backward-Oriented Reasoning. *Chem. Educ. Res. Pract.* **2018**, *19* (1), 42–59. <https://doi.org/10.1039/C7RP00124J>.
- (86) 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.* **2023**, *100* (5), 1763–1776. <https://doi.org/10.1021/acs.jchemed.2c00955>.

- (98) Creswell, J. W. *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*; Pearson: Boston, MA, USA, 2012.
- (99) Petty, R.; Wegener, D. The Elaboration Likelihood Model: Current Status and Controversies. In *Dual-process theories in social psychology*; 1999; pp 41–72.
- (100) Cottrell, S. *Critical Thinking Skills : Developing Effective Analysis and Argument*, Second edition.; Palgrave study skills; Palgrave Macmillan: Basingstoke, Hampshire, 2011.
- (101) Allchin, D. Error Types. *Perspect. Sci.* **2001**, 9, 38–58.
<https://doi.org/10.1162/10636140152947786>.
- (102) Ryder, J. Identifying Science Understanding for Functional Scientific Literacy. *Stud. Sci. Educ.* **2001**, 36 (1), 1–44. <https://doi.org/10.1080/03057260108560166>.
- (103) Ing, K.; Karr, S.; Brankreun, M. *Environmental Science for a Changing World (Canadian Edition)*; W. H. Freeman, 2013.
- (104) King’s Centre for Visualization in Science. *SOCKit*. <https://applets.kcvs.ca/socket/> (accessed 2024-06-14).
- (105) Patton, M. Q. *Qualitative Research & Evaluation Methods*; SAGE Publications: Los Angeles, CA, 2014; Vol. 4.
- (106) Saldaña, J. *The Coding Manual for Qualitative Researchers*, 3rd ed.; SAGE Publications, Inc.: Thousand Oaks, California, 2016.
- (107) 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.
- (108) Szozda, A. R.; Lalani, Z.; Behroozi, S.; Mahaffy, P. G.; Flynn, A. B. “Systems Thinking (ST) Encourages a Safe Space to Offer Different Perspectives and Insights”: Student Perspectives and Experiences with ST Activities. *J. Chem. Educ.* **2024**, 101 (6), 2290–2307.
<https://doi.org/10.1021/acs.jchemed.4c00080>
- (109) American Chemical Society. *Introduction to Systems Thinking in Chemistry*.
<https://www.acs.org/greenchemistry/students-educators/learning-modules/systems-thinking.html> (accessed 2024-06-28).
- (110) International Union of Pure and Applied Chemistry (IUPAC). *Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+)*. <https://iupac.org/project/2020-014-3-050/> (accessed 2024-03-15).

Chapter 6: An educational framework for teaching chemistry using a systems thinking approach

6.1 Introduction to the research presented in this chapter

My experiences and perspectives of the work completed in this chapter resonate strongly with words by Helen Keller, “Alone, we can do so little; together, we can do so much”. While previous chapters have described research projects I led as a chemistry education researcher in the Flynn Research Group, this chapter describes a project I contributed independently from my research with the Flynn Research Group. The opportunity to collaborate with other chemistry education researchers and scholars was a huge turning point for me in my academic career, where I felt my work and ST knowledge was valued and I was able to widen the scope of my educational efforts more globally.

In the summer of 2023, I was invited to be a member of the IUPAC Systems Thinking in Chemistry for Sustainability: 2030 and Beyond project. I received this invitation due to my expertise on ST developed over the years and my ST contributions to the literature.¹ The committee for this project consists of many leading international experts on ST from academia and the industry; I am currently the only graduate student who serves on this committee. This project builds on the momentum and success of the previous IUPAC ST in chemistry education project and is focused on (1) sustainability, (2) formal chemistry education, and (3) chemical industry.¹

Part of my role has involved working on a subgroup to develop a Sustainability and Systems Thinking in Chemistry Education website that provides open access to information, tools, and educational resources on ST and sustainability to the chemistry and chemistry education communities.² Here, I have been able to share my expertise in ST and our chemistry education research, to curate sections of the website on ST opportunities and challenges as well as teaching resources and assessment.

One of the outcomes of this website was the development of an educational framework to guide the planning, implementation, and assessment of ST approaches in chemistry courses.³ This project emerged from the need for curriculum reform efforts to embed ST into existing chemistry curricula. Chemistry educators have indicated they need a step-by-step guide on how to implement ST into their courses.⁴ I worked collaboratively with a world-renowned expert in chemistry education, Vicente Talanquer, to develop this educational framework, and collaborated with other international working group members to create example resources to complement the framework.

This project allowed me to mobilize the findings of my research into the design of this educational ST framework and develop skills in curriculum development. This framework emphasizes that ST learning

activities should: “(1) foster and enable students active and interactive participation by integrating collaborative activities to achieve ambitious learning goals, and (2) help students connect what they already know to the new ideas introduced in class and create opportunities for students to share their knowledge, perspectives, and experiences, embracing diversity and fostering inclusion”.³ These recommendations align with the implications of our research in Chapter 4.

In this chapter, the reader will learn about one potential way of planning, implementing, and assessing ST in chemistry courses by following specific tasks that are guided by four overarching learning outcomes. Creating educational materials is difficult without sufficient specific examples or access to educational resources (e.g., textbooks) that align with this framework. To support educators, we created a series of examples of using the framework that can serve as guides or references while creating new learning and teaching materials, helping to minimize educational barriers and develop instructional change for ST in chemistry education.⁵

6.2 Reference for introduction

- (1) International Union of Pure and Applied Chemistry (IUPAC). *Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+)*. <https://iupac.org/project/2020-014-3-050/> (accessed 2024-03-15).
- (2) *Sustainability and Systems Thinking in Chemistry Education*. Sastice.com (accessed 2024-06-13).
- (3) Talanquer, V.; Szozda, A. R. An Educational Framework for Teaching Chemistry Using a Systems Thinking Approach. *J. Chem. Educ.* **2024**, *101* (5), 1785–1792. <https://doi.org/10.1021/acs.jchemed.4c00216>.
- (4) 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>.
- (5) IUPAC Systems Thinking in Chemistry for Sustainability: 2030 and Beyond (STCS 2030+) project. *Systems Thinking in Chemistry Education*. <https://sites.google.com/view/sastice/home> (accessed 2024-07-08).

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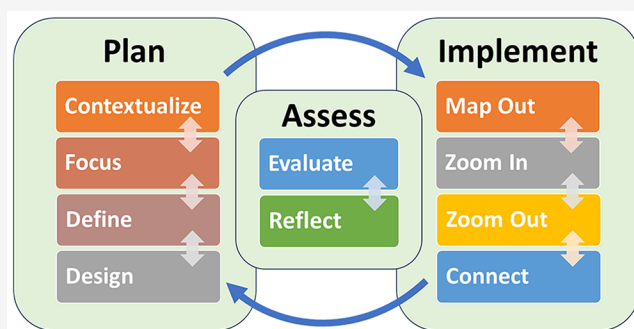
ABSTRACT: Chemical ways of knowing, thinking, and acting are critical for finding solutions to complex global challenges and achieving the United Nations' Sustainable Development Goals. Reorienting chemistry education using a systems thinking (ST) perspective can help us better equip students with the knowledge, skills, and dispositions that they need to contribute to these efforts. To support this needed educational reform, we describe in this article an educational framework that can guide and facilitate the work of chemistry educators when planning, implementing, and assessing chemistry units, modules, or lessons using an ST approach. This framework is an outcome of the IUPAC Systems Thinking in Chemistry for Sustainability: 2030 and Beyond (STCS 2030+) project, which seeks to provide resources and tools on ST and sustainability to the chemistry and chemistry education communities.

KEYWORDS: First-Year Undergraduate/General, High School/Introductory Chemistry, Second-Year Undergraduate/General, Upper-Division Undergraduate, Graduate Education/Research

INTRODUCTION

Modern societies and our planet face several socio-environmental challenges, which include guaranteeing access to clean drinking water, ending hunger, reducing greenhouse gas emissions, fighting new and re-emerging diseases, and achieving sustainable development.¹ Addressing these issues will require the collaborative actions of citizens and professionals who (1) can understand these problems, (2) are prepared to respond and manage complexity, uncertainty, and rapid change, and (3) can help achieve the United Nations' Sustainable Development Goals.² Chemical knowledge, reasoning, and practices will be crucial to confront these problems,³ but to better equip current students with the knowledge, skills, and dispositions, they need to contribute to these efforts; chemistry educators must take immediate and definitive actions to transform curricula, instructional methods, and assessment practices to align them with these ambitious goals.^{4–6}

The complex task of analyzing, understanding, and tackling global issues demands that all students, particularly those interested in science, technology, engineering, and math (STEM) careers, achieve four fundamental learning outcomes (Figure 1): (1) meaningfully understand central ideas in chemistry,^{7–11} (2) know how to apply science and engineering practices to investigate phenomena and design solutions,¹² (3) develop systems thinking (ST) skills to analyze the systems of



and sustainability to the chemistry and chemistry education communities.

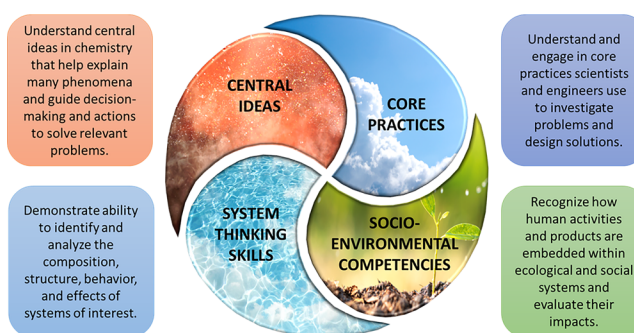


Figure 1. Fundamental learning outcomes in a systems thinking approach to chemistry education (all images belong to the public domain).

interest,^{13–15} and (4) act with socio-environmental responsibility.^{6,16,17}

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The first two learning outcomes align with the educational goals of the Next Generations Science Standards (NGSS)¹⁸ which also expect students to learn to reason using a set of crosscutting concepts that support a systemic perspective (e.g., “systems and system models,” “patterns,” “stability and change”). Nevertheless, in the approach we advocate, crosscutting concepts are integrated and serve as foundational in the development of ST skills that support the application of central ideas and core practices in chemistry to analyze, understand, and evaluate solutions to socio-environmental issues with a sustainability lens. The educational framework for teaching chemistry using the ST approach described in this contribution seeks to guide and facilitate the planning, implementation, and assessment of chemistry units, modules, or lessons that achieve this integration in meaningful and effective ways. Our framework offers a blueprint for creating opportunities to learn chemistry as a powerful way of knowing, thinking, and acting to build a safe, healthy, and sustainable world. This framework is an outcome of the IUPAC Systems Thinking in Chemistry for Sustainability: 2030 and Beyond (STCS 2030+) project which seeks to provide resources and tools on ST and sustainability to the chemistry and chemistry education communities. Additional resources can be found on the SaSTICE (Sustainability and Systems Thinking in Chemistry Education) Website for this project.¹⁹

SYSTEMS THINKING IN CHEMISTRY EDUCATION

In recent years, there has been an increasing number of calls to reorient chemistry education using ST,^{4–6,20–23} conceptualized as a way of reasoning about complex phenomena caused by the dynamic interactions of interdependent components (a system) operating at multiple scales, from the submicroscopic to the macroscopic scales.^{13–15,21} Finding solutions to global sustainability challenges requires citizens and professionals who have a fundamental understanding of how these issues emerge from the dynamic interaction between chemical, physical, biological, and environmental subsystems (Earth subsystems) and social, political, and economic subsystems (Human subsystems). From this perspective, continuing to teach chemistry as a static body of theoretical knowledge disconnected from the issues that affect students’ lives and their personal, professional, and civic interests is likely to deem the study of our discipline irrelevant or subsidiary.

Reorienting chemistry education using an ST approach may have diverse benefits:⁵

- Providing a more unified and integrated view of chemical knowledge by building connections between central ideas in the discipline.
- Integrating central ideas, disciplinary practices, systems thinking, and socio-environmental competencies into the preparation of future citizens and professionals.
- Fostering meaningful learning by actively engaging students in the learning process through the analysis, discussion, and reflection of relevant personal and societal issues.
- Creating more inclusive learning environments where students can share prior knowledge and experiences relevant to the issues under consideration.²⁴
- Building and strengthening interdisciplinary connections enabling students to reason across disciplinary boundaries.
- Creating more positive attitudes toward chemistry by projecting this discipline as a “science for society” that

enables the development of solutions to global problems and advances sustainable development.

Ultimately, we see reorienting chemistry education through ST with a focus on sustainable development as a moral imperative in a world facing major global challenges with chemical origins and potential chemical solutions.

EDUCATIONAL FRAMEWORK

To guide and facilitate the application of an ST lens in the planning, implementation, and assessment of chemistry units, modules, or lessons, we propose using the educational framework summarized in Figure 2 and described in the

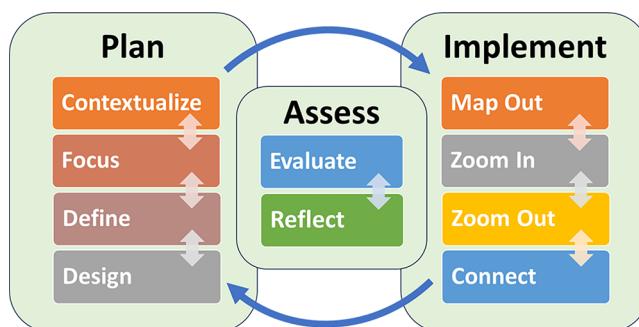


Figure 2. Educational framework for teaching chemistry using a systems thinking approach.

following subsections. The different tasks outlined in the framework are interconnected and may need to be revisited in iterative ways when building, implementing, and evaluating units of instruction. A specific example of a unit of instruction designed using this framework is summarized in Table 1. We suggest referring to this table while analyzing the different tasks highlighted in Figure 2 and described in the following sections. Additional examples of the implementation of the framework and their associated educational resources can be found in the “Systems Thinking in Chemistry Education” sub-Web site²⁵ from the IUPAC SaSTICE project.¹⁹

Planning Stage

When planning to teach chemistry using an ST approach, we suggest completing four major tasks, including (1) selecting a relevant context to anchor instruction (**Contextualize**), (2) identifying subsystems in interaction and define the scope of the lesson or unit of instruction (**Focus**), (3) delineating multi-dimensional learning outcomes (**Define**), and (4) building a meaningful and engaging instructional sequence (**Design**).

Contextualize. Most chemistry educators recognize the importance of connecting the concepts and ideas introduced in class to problems or phenomena that may interest their students. However, they often make these connections sporadically. They may begin a lesson by pointing to a relevant issue to catch their students’ attention and motivate them. They may discuss an interesting example at the end of a lesson to illustrate the application of what students learned.^{26,27}

When adopting an ST approach to chemistry teaching, one must integrate the context in more meaningful ways.^{28,29} The problem or phenomenon to analyze should guide and structure the presentation of the central chemical concepts and ideas that we want students to learn. It should create opportunities for students to comprehend an issue facing our planet, their communities, or their personal lives; it should help them

Table 1. Example of the Application of the ST Educational Framework in the Planning, Implementation, and Assessment of a Chemistry Unit Using Greenhouse Gases as a Context

Stage	Task	Example
Plan	Contextualize	The analysis of the composition and structure of greenhouse gases (GHGs), their interactions with electromagnetic radiation in the atmosphere, and the effects of those interactions on average temperatures on our planet presents an ideal context to introduce and apply central chemical concepts such as electronegativity, partial charge, bond polarity, molecular polarity, and light-matter interactions using an ST perspective. This context can be used to explore the central idea that the composition and structure of chemical substances at the submicroscopic level determine their physical and chemical properties.
	Focus	This lesson will focus on the analysis of the chemical composition and structure of GHGs and the consequences of their interactions with the infrared solar radiation reflected by Earth on our planet's temperature.
	Define	As an integrated learning outcome for this unit, students should be able to analyze a set of commonly used substances (e.g., refrigerants) and determine whether they may act as GHGs if they escape into the atmosphere, predict and justify their light-matter interactions based on molecular models, analyze their potential global warming effects based on data, and propose and evaluate the effectiveness of strategies to reduce these emissions considering environmental, social, and economic factors.
	Design	The unit of instruction is designed using a sequence of activities that students are expected to complete in small collaborative groups and then share their ideas in whole class discussions. In these activities, students are asked to analyze data (e.g., types of radiation emitted by the Sun and our planet), make models (e.g., build models of molecular polarity), and generate explanations (e.g., explain why not all atmospheric components absorb IR radiation). Activities also allow students to develop systems thinking skills (e.g., analyze the composition, structure, behavior, and effects of relevant interacting systems) and build socio-environmental competencies (e.g., analyze specific actions to reduce GHG emissions).
Implement	Map Out	During this stage of the unit, students are asked to use their prior knowledge and experiences to build an initial system map identifying major atmospheric components and their interactions with diverse subsystems (e.g., radiation from the Sun and Earth, living organisms, and human communities). Students use online tools, like SOCKit, ³¹ to build their maps.
	Zoom In	In this part of the unit, students identify important atmospheric components (O ₂ , N ₂ , CO ₂ , H ₂ O) and explore properties that affect their interaction with electromagnetic radiation. Students are introduced to the concepts of bond polarity and molecular polarity and use an interactive tool to infer the polarity of different chemical entities in the atmosphere. Later in the lesson, the students explore how bond and molecular polarity determine whether molecules absorb infrared radiation and, thus, may contribute to global warming.
	Zoom Out	Once students understand the targeted phenomenon at the submicroscopic level, they are asked to analyze the emission spectra for the Sun and Earth in combination with the absorption spectra of H ₂ O and CO ₂ to infer consequences for our planet.
	Connect	In this last stage of the unit, students engage in activities that allow them to apply their knowledge in making decisions and suggesting individual or collective actions directed at addressing the environmental problem under consideration.
Assess	Evaluate	The different activities interspersed through the unit create opportunities to formatively assess student learning and provide specific feedback to advance their understanding to meet the lesson's learning objectives. As a summative assessment, students are asked to analyze the composition and structure of less commonly known GHGs in our atmosphere, predict their properties, and analyze their potential global warming effects.
	Reflect	The formative assessment data gathered during the lesson is used to critically reflect on aspects of the unit that need to be modified to support student learning of the central chemical ideas, core practices, systems thinking skills, and socio-environmental competencies that are targeted.

understand how chemical knowledge and chemical ways of knowing, thinking, and acting can help us make sense of the problem and devise and evaluate potential solutions.³⁰

Focus. Socio-environmental problems in our world result from the interaction of diverse and complex factors. This complexity creates challenges when a unit of instruction focused on these issues is planned. What factors are most important to explore? What interactions should be analyzed? What subsystems in the interaction should we consider? When using an ST approach, one must decide what aspects of a problem to consider and focus on. For example, what chemical, physical, or biological components in the interaction will be studied? What environmental, economic, social, or political influences and effects will be identified and discussed? The designed educational experience should help students to meaningfully comprehend the issue. Attempting to explore a problem considering all of the factors will likely result in superficial content coverage and overwhelm students.

To define the focus of a chemistry lesson, one could ask: What central chemical ideas do we expect our students to learn? What competencies do we want them to develop? What aspects of the problem under analysis are students most interested in learning about and which will be most relevant to them? Connecting with students' prior knowledge, experiences, and interests has shown to improve motivation toward learning chemistry content.³² The scope of chemistry lessons built using an ST approach should go beyond the chemistry content.⁶ However, the scope should be carefully defined to ensure that students can comprehend the selected aspects of the target problem in meaningful ways.

Define. When planning chemistry lessons using an ST approach, one must define learning outcomes that integrate four major components:

- The central ideas in chemistry we expect the students to learn.
- The core science and engineering practices in which students will engage.
- The systems thinking skills that students will practice.
- The socio-environmental competencies that students will develop.

The identification of central ideas in chemistry is facilitated by analyzing existing resources published by diverse authors.^{7–11} Central ideas in a discipline provide the basis for the organization and development of an important set of concepts. They help build explanations, make predictions about many phenomena and systems, and guide decision-making and the design of actions to solve relevant problems. For example, a central idea in chemistry states that the macroscopic properties of substances emerge from the dynamic interaction of myriads of particles at the submicroscopic level, and these interactions depend on the composition and structure of such particles. This idea can serve as an organizer for the introduction of a variety of chemistry concepts and guide student reasoning in explaining or making sense of the properties of a variety of systems.

Core science and engineering practices describe behaviors in which scientists and engineers engage to investigate problems and design solutions.¹² They include developing and using models, planning and carrying out investigations, analyzing and interpreting data, engaging in argument from evidence and building explanations, and evaluating and communicating information.

Systems thinking skills allow students to identify and analyze the composition, structure, behavior, and effects of systems of interest as summarized in Figure 3.^{13–15} Providing opportunities

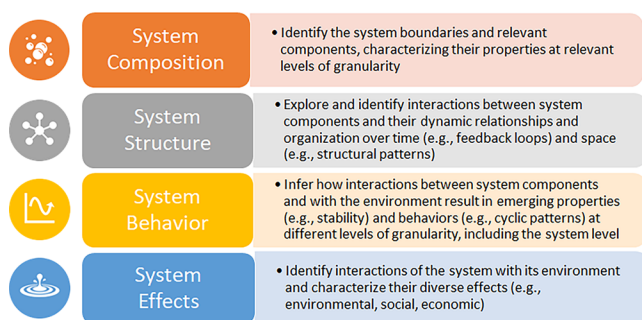


Figure 3. Major attributes of a system and associated systems thinking skills.

for students to practice and build ST skills in diverse contexts can help them use and transfer their knowledge and skills effectively to other situations where they are needed.²

Finally, socio-environmental competencies enable students to recognize how human activities and products are embedded within ecological and social systems and to evaluate their impacts.^{16,17} They equip students to analyze problems and

evaluate solutions with empathy, ethical consideration, and cultural awareness, paying attention to issues of social and environmental justice.

Overall, the learning outcomes that we define in a chemistry unit, lesson, or module using an ST approach should aspire one to integrate central ideas, core practices, systems thinking skills, and socio-environmental competencies in seamless ways to guide the design of classroom activities and assessment tasks that effectively foster and scaffold student learning in all dimensions.

Design. Chemistry lessons designed using an ST approach should meaningfully engage students in the learning process. This can be accomplished using evidence-based instructional models and strategies known to foster student understanding. For example, units of instruction may be designed to include several learning cycles where students explore a phenomenon, are introduced to relevant chemical ideas, and apply these ideas in diverse ways.³³ These designed learning activities should (1) foster and enable students active and interactive participation by integrating collaborative activities to achieve ambitious learning goals,^{34,35} (2) help them connect what they already know to the new ideas introduced in class and create opportunities for all students to share their knowledge, perspectives, and experiences, embracing diversity and fostering inclusion,^{24,36} (3) ask students to analyze and interpret data, seeking to identify patterns in the properties and behavior of the systems of interest, and (4) equip

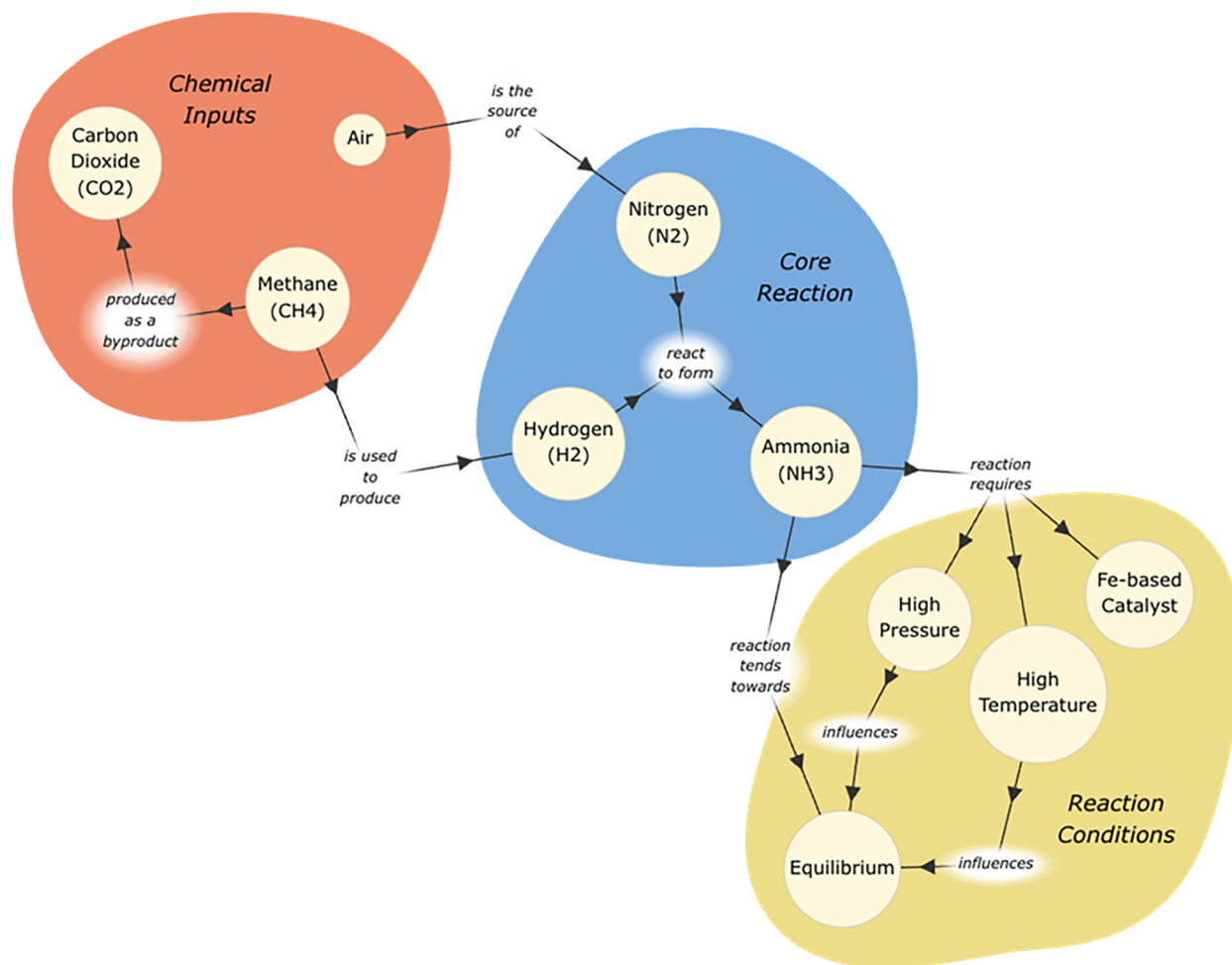


Figure 4. A SOCME (System-Oriented Concept Map Extension) created with SOCKit is a way to visualize the components and interactions of a system using a concept map.

them to build and use chemical models to make predictions, support arguments, and generate explanations of relevant phenomena.¹²

Through collaborative engagement, learning activities should help students comprehend the nature, scale, and importance of the socio-environmental issue under analysis while learning the chemical concepts and ideas that help us understand and address the problem. Additionally, learning activities must create opportunities for students to practice ST skills to analyze the composition, structure, behavior, and effects of relevant interacting systems and to develop socio-environmental competency by analyzing and evaluating diverse factors, including social, environmental, economic, and political considerations.

Overall, during the planning of units of instruction using an ST approach, chemistry educators should make intentional design decisions that build and strengthen meaningful relationships between students and the chemistry content, between students and the context in which they live, between students and other students, and between students, educators, and the educational resources they have to offer.³⁷

Implementing Stage

During the implementation of lessons, modules, or units of instruction using an ST approach, we suggest organizing the content and activities designed in the planning stage in a sequence that helps students (1) develop an understanding of the nature and scope of the system under analysis (**Map Out**), (2) identify main chemical components and characterize major interactions between them (**Zoom In**), (3) recognize system level properties and behaviors that emerge from the interactions between components as well as examine major factors affecting them (**Zoom Out**), and (4) explore the effects of interactions between relevant subsystems (e.g., chemical and biological to social and economic subsystems) (**Connect**).

Map Out. When chemistry lessons are implemented using an ST approach, we suggest beginning with activities that help students understand the nature and scope of the system under analysis. These activities should engage students in a first analysis of the socio-environmental problem or phenomenon of interest and help them recognize the types of subsystems in interaction (e.g., hydrosphere and atmosphere) and the factors that affect them. These factors may be chemical, physical, biological, environmental, social, political, or economic. The goal of these introductory activities is to map out the landscape of variables and factors to consider, creating the first overall view of the nature and complexity of the problem or phenomenon to be analyzed.

To meet these objectives, students can complete introductory reading assignments on the subject. They may watch short videos describing the problems and potential solutions. They may analyze some data to identify the relevant patterns. To summarize their initial insights and understandings, students can collaboratively build diagrams highlighting the major actors and their interactions. For example, they can create or complete system maps that visually depict the main components of the system of interest and their relationships.^{38,39} For this purpose, students can use tools available freely online that facilitate this work, such as the SOCKit³¹ developed by the King's Centre for Visualization in Science (see [Figure 4](#)). Overall, before delving into the chemical roots of the problem, students should develop an overarching understanding of its scope and complexity.

Zoom In. Once students develop an initial understanding of the socio-environmental issue to analyze, educators can delve into the chemical concepts and ideas that help to make sense of the problem and propose solutions. For this purpose, they should create opportunities for students to explore the problem or phenomenon using chemical models at appropriate levels of granularity, which requires zooming in across different scales in space and time, from the macroscopic to the submicroscopic levels and from processes and events taking many years to only a few seconds. The nature and extent of zooming in should be guided by the outlined learning outcomes.

During this phase, students should be able to identify the major chemical components involved in the systems and processes under consideration.^{14,15} They should recognize their properties and interactions and use this information to build causal stories to predict the behavior of the system of interest and explain the targeted phenomena. Developing students' ability to generate these mechanistic explanations⁴⁰ is critical for understanding structure–property relationships in chemistry,^{41,42} specifically, understanding how and why the composition and structure of chemical components determine the properties and behavior of a chemical system.

We can foster student reasoning in this area by using a variety of interactive visualization and simulation tools freely available online, such as the Chemical Thinking Interactives,⁴³ KCVS Visualizations,⁴⁴ Molecular Workbench,⁴⁵ and PhET Interactive Simulations.⁴⁶ As we work with students developing and applying chemical models at various scales, we should help them comprehend how to use information about the composition and structure of different chemical entities to predict, for example, which will be more stable under certain conditions, what may react with each other and undergo a chemical transformation, and which products are most likely to result from these interactions. Ultimately, rather than presenting chemistry as a large body of knowledge that students should memorize, we should ensure that our learning activities help them conceptualize chemistry as a powerful way of knowing, thinking, and acting in the world.⁴⁷

Zoom Out. In traditional chemistry courses, educators commonly analyze chemical systems composed of a few particles. They may, for example, study the properties of small molecules made of a few atoms. They may represent chemical reactions involving a few molecules of reactants and products and explore phenomena that occur in a few seconds or, at most, in a few hours. Additionally, the properties and behaviors of chemical substances are typically analyzed in segmented ways, discussing, for example, stoichiometric issues in one unit and energetic or kinetic considerations in others. However, the complex problems affecting our world are driven by processes occurring across multiple scales and dimensions (e.g., composition, energy, and time). Often, one cannot attribute many of the properties and behaviors of the systems of interest to one or a few components and constrain the analysis to a single variable or dimension. Instead, properties emerge from the interactions of unimaginably large numbers of diverse particles distributed all over the planet. The processes of interest occur on time scales of months or years, and their causes typically have distant origins in space and time. Their analysis thus demands crossing different levels of granularity and physical dimensions and integrating diverse types of knowledge.

Consequently, when teaching chemistry using an ST approach, educators must zoom out from the submicroscopic scale to the macroscopic world. They should guide students in

applying chemical ideas and ways of thinking to make sense of large-scale phenomena, such as matter and energy cycles in systems of interest or positive and negative feedback loops controlling or affecting a system's stability. Students should be able to use their chemical knowledge to build mechanistic explanations about a complex system's emergent properties, such as changes in marine life due to increased concentrations of carbon dioxide in the atmosphere or the development of antibiotic resistance due to overuse and misuse of these medications.

As zooming in on a system's chemical composition and structure is critical to understanding the components that affect its behavior, zooming out is needed for understanding how the interactions and organization of those entities lead to the global challenges facing our planet and identifying solutions in which chemistry has a central role to play.

Connect. Traditional chemistry lessons are often packed with content that little time is left for students to integrate and reflect on their learning. When teaching chemistry using an ST approach, educators must ensure that students have these opportunities. Closing activities should allow students to summarize the main understandings developed during the lesson. These tasks should help them reinforce knowledge connections, step back to look at the whole picture, and reflect on what they have learned. Closing activities should also open room for students to highlight connections between the different aspects of the socio-environmental issue in interaction, reflect on the benefits, costs, and risks of strategies proposed to address detected problems, and apply their knowledge to suggest individual or collective actions directed at addressing the issue under consideration.

To achieve these goals, educators may ask students to build a summary table or report in which they describe major patterns in the system under analysis, the chemical causes and mechanisms discussed in class, and the interconnections between relevant subsystems.³⁵ They may also suggest that students revise the initial system map they built at the beginning of the lesson. This map should be modified or enriched by using the new understandings that students have developed. Educators and students could also organize presentations, class discussions, or debates to share ideas about how to apply chemical knowledge and ways of thinking to address the targeted issue. What individual and collective actions may be implemented? What potential solutions would ensure safe and equitable outcomes? What actors and processes at any level, including chemical, biological, social, or political, should be influenced to attain sustainability goals? Through these tasks, students should recognize the extent and value of what they have learned and demonstrate the depth of their understanding.

Assessing Stage

When assessing lessons, modules, or units of instruction using an ST approach, we suggest regularly engaging students in activities to evaluate their understanding (**Evaluate**) and critically reflecting on how instruction may better support student learning (**Reflect**).

Evaluate. Student learning should be formatively assessed on a regular basis to provide feedback that helps students advance in their understanding and gather information that can be used to improve the lesson.⁴⁸ Student understanding should also be evaluated using summative assessments designed to measure attainment of integrated learning goals.⁴⁹

Implementing formative assessment regularly during chemistry lessons is crucial to advance student understanding and inform instruction. These assessments can be formal, through planned in-class activities, or informal, by students interacting on the fly. Their implementation usually follows a cycle of eliciting students' ideas, interpreting student thinking, and implementing actions to redirect or advance student understanding.⁵⁰

Educators can elicit students' prior knowledge and current ideas by posing probing questions and encouraging students to elaborate on their answers. They should seek to interpret their ideas to identify conceptions that may serve as springboards for further learning, or they may need to discuss to redirect students' thoughts. Based on these inferences, educators should provide students with feedback in the form of specific suggestions on what ideas to add or reconsider and what next steps to follow. This feedback should come not only from the educator but also from other students. Formative assessment should respectfully involve all learners to advance the group's understanding.

As part of the evaluation process, educators must also design and implement summative assessments to determine how well students have met the learning outcomes. When teaching chemistry using an ST approach, these outcomes are multi-dimensional. Thus, the summative assessments should reveal whether students can apply the targeted central ideas, science and engineering practices, systems thinking skills, and socio-environmental competencies in integrated ways. Rather than relying on traditional exams with questions that measure isolated pieces of knowledge, we suggest using integrated assessments that ask students to transfer and apply what they have learned to analyze a problem or phenomenon related to the one explored in class.⁴⁹ Overall, we should consider formative and summative assessments as both learning experiences for the students and opportunities for educators to gather data about student understanding.

Reflect. Formative and summative assessments are powerful tools for collecting data on student learning during a lesson. Educators can use these data to evaluate the effectiveness of the instructional sequence, reflect on changes that would foster student learning, and take actions that strengthen the lesson activities.⁵¹ Educators should use these data to critically reflect on aspects of the lesson that they can modify to enhance student learning. This reflection demands paying attention not only to cognitive but also to affective issues impacting student learning and recognizing and affecting barriers acting at the individual and classroom levels.^{52,53}

An educator's reflection does not need to be a solitary activity. When teaching chemistry using an ST approach, chemistry educators benefit from the interaction with people from other areas. The complex issues used to structure the lessons typically require applying knowledge and ways of thinking from various fields, such as other natural sciences, the social sciences, and the humanities.^{28,29} Understanding and addressing the grand challenges facing our planet require an interdisciplinary approach. Ultimately, it would be ideal to integrate the entire school curriculum to prepare students who can think about complex issues and problems from different disciplinary perspectives.

■ FINAL COMMENTS

The educational framework described in this paper should not be conceived as a rigid sequence of steps that must be followed in the stated order. It seeks rather to highlight important areas

consideration and reflection when planning, implementing, and assessing units of instruction using an ST approach. For example, it may be best to design formative and summative assessments during the planning stage once the learning outcomes are defined. Educators who adopt this framework should adapt it to their contexts and the characteristics and needs of their students.

We recognize the challenge of developing educational materials without many specific examples that can guide our work or access to educational resources, such as textbooks, aligned with the desired approach. Thus, we encourage chemistry educators interested in reorienting their teaching using an ST perspective to review the examples available online, such as the materials developed by the SaSTICE project from the IUPAC^{19,25} and those created by the ACS Green Chemistry Institute.⁵⁴ These resources can serve as guides and references while creating new materials.

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Notes

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REFERENCES

- (1) Richardson, K.; Steffen, W.; Lucht, W.; Bendtsen, J.; Cornell, S. E.; Donges, J. F.; Driike, M.; Fetzer, I.; Bala, G.; von Bloh, W.; et al. Earth Beyond Six of Nine Planetary Boundaries. *Sci. Adv.* **2023**, *9* (37), eadh2458.
- (2) United Nations. *United Nations' Sustainable Development Goals*; 2023; <https://sdgs.un.org/goals> (accessed 2024-01-25).
- (3) Matlin, S. A.; Mehta, G.; Hopf, H.; Krief, A. One-World Chemistry and Systems Thinking. *Nat. Chem.* **2016**, *8* (5), 393–398.
- (4) 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.
- (5) Mahaffy, P. G.; Krief, A.; Hopf, H.; Mehta, G.; Matlin, S. A. Reorienting Chemistry Education through Systems Thinking. *Nature Reviews Chemistry* **2018**, *2* (4), 0126.
- (6) Talanquer, V.; Bucat, R.; Tasker, R.; Mahaffy, P. G. Lessons from a Pandemic: Educating for Complexity, Change, Uncertainty, Vulnerability, and Resilience. *J. Chem. Educ.* **2020**, *97* (9), 2696–2700.
- (7) Gillespie, R. J. The Great Ideas of Chemistry. *J. Chem. Educ.* **1997**, *74* (7), 862.
- (8) Atkins, P. Chemistry: The Great Ideas. *Pure Appl. Chem.* **1999**, *71* (6), 927–929.
- (9) Cooper, M. M.; Posey, L. A.; Underwood, S. M. Core Ideas and Topics: Building up or Drilling Down? *J. Chem. Educ.* **2017**, *94* (5), 541–548.
- (10) Holme, T.; Luxford, C.; Murphy, K. Updating the General Chemistry Anchoring Concepts Content Map. *J. Chem. Educ.* **2015**, *92* (6), 1115–1116.
- (11) Talanquer, V. Central Ideas in Chemistry: An Alternative Perspective. *J. Chem. Educ.* **2016**, *93* (1), 3–8.
- (12) National Research Council. *A Framework for K-12 Science Education*; The National Academies Press: Washington, DC, 2012.
- (13) 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.
- (14) Momsen, J.; Speth, E. B.; Wyse, S.; Long, T. Using Systems and Systems Thinking to Unify Biology Education. *CBE Life Sci. Educ.* **2022**, *21* (2), es3.
- (15) 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.
- (16) The Lemelson Foundation. *The Engineering for One Planet Framework: Essential Sustainability-Focused Learning Outcomes for Engineering Education*; Portland, OR, 2022.
- (17) Wiek, A.; Withycombe, L.; Redman, C. L. Key Competencies in Sustainability: A Reference Framework for Academic Program Development. *Sustainability Science* **2011**, *6* (2), 203–218.
- (18) National Research Council. *Next Generation Science Standards*; The National Academies Press: Washington, DC, 2013.
- (19) IUPAC Systems Thinking in Chemistry for Sustainability: 2030 and Beyond (STCS 2030+) project. *Sustainability and Systems Thinking in Chemistry Education*; SaSTICE, 2024; <https://sastice.com/> (accessed 2024-02-21).
- (20) Pazicni, S.; Flynn, A. B. Systems Thinking in Chemistry Education: Theoretical Challenges and Opportunities. *J. Chem. Educ.* **2019**, *96* (12), 2752–2763.
- (21) Orgill, M.; York, S.; MacKellar, J. Introduction to Systems Thinking for the Chemistry Education Community. *J. Chem. Educ.* **2019**, *96* (12), 2720–2729.
- (22) Tümay, H. Systems Thinking in Chemistry and Chemical Education: A Framework for Meaningful Conceptual Learning and Competence in Chemistry. *J. Chem. Educ.* **2023**, *100* (10), 3925–3933.
- (23) Bozkurt, E. A Bibliometric Analysis of Systems Thinking Research in Science Education 1991–2022. *Sci. Educ. Int.* **2023**, *34* (3), 225–234.
- (24) Szozda, A. R.; Lalani, Z.; Behrooz, S.; Mahaffy, P. G.; Flynn, A. B. Systems Thinking Encourages a Safe Space to Offer Different Perspectives and Insights. *ChemRxiv* **2024**, DOI: 10.26434/chemrxiv-2024-twmpk.
- (25) IUPAC Systems Thinking in Chemistry for Sustainability: 2030 and Beyond (STCS 2030+) project. *Systems Thinking in Chemistry Education*; 2024; <https://sites.google.com/view/sastice/home> (accessed 2024-01-24).
- (26) Sjöström, J.; Talanquer, V. Humanizing Chemistry Education: From Simple Contextualization to Multifaceted Problemization. *J. Chem. Educ.* **2014**, *91* (8), 1125–1131.
- (27) Gilbert, J. K. On the Nature of “Context” in Chemical Education. *Int. J. Sci. Educ.* **2006**, *28* (9), 957–976.
- (28) Ewing, M.; Sadler, T. D. Commentary: Socio-Scientific Issues Instruction: An Interdisciplinary Approach to Increase Relevance and Systems Thinking. *Science Teacher* **2020**, *88* (2), 18–21.
- (29) Hancock, T. S.; Friedrichsen, P. J.; Kinslow, A. T.; Sadler, T. D. Selecting Socio-Scientific Issues for Teaching. *Sci. & Educ.* **2019**, *28* (6), 639–667.
- (30) Eilks, I.; Hofstein, A. *Relevant Chemistry Education: From Theory to Practice*; SensePublishers: Rotterdam, The Netherlands, 2022.

- (31) The King's Centre for Visualization in Science. *SOCKit*; 2024; <https://applets.kcvs.ca/sockit/> (accessed 2024-02-21).
- (32) King, D. New Perspectives on Context-Based Chemistry Education: Using a Dialectical Sociocultural Approach to View Teaching and Learning. *Stud. Sci. Educ.* **2012**, 48 (1), 51–87.
- (33) Abraham, M. R.; Renner, J. W. The Sequence of Learning Cycle Activities in High School Chemistry. *J. Res. Sci. Teach.* **1986**, 23 (2), 121–143.
- (34) Chi, M. T. H.; Wylie, R. The Icap Framework: Linking Cognitive Engagement to Active Learning Outcomes. *Educ. Psychol.* **2014**, 49 (4), 219–243.
- (35) Windschitl, M.; Thompson, J.; Braaten, M. *Ambitious Science Teaching*; Harvard University Press: Cambridge, MA, 2018.
- (36) Dewsbury, B.; Brame, C. J. Inclusive Teaching. *CBE Life Sci. Educ.* **2019**, 18 (2), fe2.
- (37) Moreira, P.; Talanquer, V. Exploring Relationships That College Instructors Seek to Build with Intention in Chemistry Classrooms. *Chem. Educ. Res. Pract.* **2024**, 25 (1), 225–241.
- (38) Aubrecht, K. B.; Dori, Y. J.; Holme, T. A.; Lavi, R.; Matlin, S. A.; Orgill, M.; Skaza-Acosta, H. Graphical Tools for Conceptualizing Systems Thinking in Chemistry Education. *J. Chem. Educ.* **2019**, 96 (12), 2888–2900.
- (39) Eaton, A. C.; Delaney, S.; Schultz, M. Situating Sustainable Development within Secondary Chemistry Education Via Systems Thinking: A Depth Study Approach. *J. Chem. Educ.* **2019**, 96 (12), 2968–2974.
- (40) Dood, A. J.; Watts, F. M. Mechanistic Reasoning in Organic Chemistry: A Scoping Review of How Students Describe and Explain Mechanisms in the Chemistry Education Research Literature. *J. Chem. Educ.* **2022**, 99 (8), 2864–2876.
- (41) Talanquer, V. Progressions in Reasoning About Structure–Property Relationships. *Chem. Educ. Res. Pract.* **2018**, 19 (4), 998–1009.
- (42) den Otter, M.-J.; Juurlink, L. B. F.; Janssen, F. J. J. M. How to Assess Students' Structure–Property Reasoning? *J. Chem. Educ.* **2022**, 99 (10), 3396–3405.
- (43) Chemical Thinking Curriculum. *Chemical Thinking Interactives*; 2024; <https://sites.google.com/site/ctinteractives/> (accessed 2024-01-24).
- (44) The King's Centre for the Visualization of Science. *KCVS Visualizations*; 2024; <https://www.kcvs.ca/cards.html?type=visualizations> (accessed 2024-01-24).
- (45) The Concord Consortium. *Molecular Workbench*; 2024; <http://mw.concord.org/modeler/> (accessed 2024-01-24).
- (46) University of Colorado Boulder. *PhET Interactive Simulations*; 2024; <https://phet.colorado.edu/> (accessed 2024-01-24).
- (47) Talanquer, V.; Pollard, J. Let's Teach How We Think Instead of What We Know. *Chem. Educ. Res. Pract.* **2010**, 11 (2), 74–83.
- (48) Black, P.; Harrison, C.; Lee, C.; Marshall, B.; William, D. *Assessment for Learning—Putting It into Practice*; Open University Press: Maidenhead, UK, 2003.
- (49) Lavery, J. T.; Underwood, S. M.; Matz, R. L.; Posey, L. A.; Carmel, J. H.; Caballero, M. D.; Fata-Hartley, C. L.; Ebert-May, D.; Jardeleza, S. E.; Cooper, M. M. Characterizing College Science Assessments: The Three-Dimensional Learning Assessment Protocol. *PLoS One* **2016**, 11 (9), No. e0162333.
- (50) Black, P.; Wiliam, D. Developing the Theory of Formative Assessment. *Educ. Assess. Evaluation Account.* **2009**, 21 (1), 5–31.
- (51) Machost, H.; Stains, M. Reflective Practices in Education: A Primer for Practitioners. *CBE Life Sci. Educ.* **2023**, 22 (2), es2.
- (52) Talanquer, V.; Kelly, R. Thinking and Learning in Nested Systems: The Individual Level. *J. Chem. Educ.* **2024**, 101 (2), 283–294.
- (53) Talanquer, V.; Cole, R.; Rushton, G. T. Thinking and Learning in Nested Systems: The Classroom Level. *J. Chem. Educ.* **2024**, 101 (2), 295–306.
- (54) American Chemical Society. *Green Chemistry Learning Modules*; 2024; <https://www.acs.org/greenchemistry/students-educators/learning-modules.html> (accessed 2024-02-21).

Chapter 7: Conclusions and future directions for systems thinking in chemistry education

In this chapter, I provide an overview of the key findings, implications, and limitations of the research projects presented in this thesis, as well as their significance to academic communities. I discuss future directions for investigating ST in chemistry education and I conclude with final remarks on the lessons learned from my PhD as well as advice for fellow graduate students.

7.1 Conclusions, implications, limitations, and significance of the research presented in this thesis

Chemistry has been pivotal in advancing various aspects of life, but now faces a pressing need to adapt amidst environmental crises (e.g., carbon emissions and plastics pollution), which are direct outcomes of chemical processes.^{1–4} To address these challenges, we must reimagine how chemistry is taught to empower current and future chemistry innovators.^{4,5}

Chemistry and chemistry education researchers and scholars have been promoting a systems thinking (ST) approach to highlight the centrality of chemistry in these challenges and to better equip future citizens and scientists with the knowledge and skills required to understand and tackle these complex global issues.^{3,6–16} The momentum to use a ST approach in chemistry education was initiated by the use of ST approaches in other disciplines such as Geoscience, Engineering, Environmental Science, and Biology.^{17–23} However, many of the claims on the benefits of ST from these disciplines are not supported by research evidence.^{24–42} To determine if a ST approach is beneficial or possibly not beneficial to chemistry education, rigorous evidence-based research is needed to determine the effects and impacts of a ST approach in chemistry education.

My doctoral research has significantly contributed to this need for evidence-based research on ST by using qualitative research methods to investigate educators' and students' perspectives and experiences of a ST approach in chemistry education.

Our first project (Chapter 2) identified specific aspects related to educators' knowledge and beliefs about ST, educators' experiences for implementing ST, and personal and contextual factors that experts and administrators can address to reduce barriers for the implementation of ST in chemistry education.⁷ At the time of conducting this research, other chemistry educators had published on educators' perspectives of ST as well as the opportunities and challenges of ST.^{43–46} Our research was the first to use an educational change model for understanding the complex interconnected factors that enable or

hinder chemistry educators' willingness and ability to implement ST. Investigating the complexity of educator factors that influence ST adoption needs to be understood if ST approaches are to be successfully integrated into chemistry education. Surveying a group of 56 secondary and postsecondary chemistry educators from ten different countries we found that educators generally reported (1) a low level of knowledge on ST (i.e., educators' knowledge), (2) their willingness to implement ST depends on the availability of teaching resources, curriculum coverage, research-based evidence, and time to learn and implement ST (i.e., contextual factors), and (3) they a need to see an alignment of a ST approach with their current teaching values and approaches (i.e., personal factors).⁷ These three findings negatively influenced educators' willingness to adopt a ST approach suggesting that efforts of change need to be made toward educators' knowledge, contextual factors, and personal factors.⁷ In alignment with these findings, we found barriers related to educators' knowledge (i.e., limited expertise in ST) and contextual factors (i.e., limited time to learn and teach ST, limited teaching resources and assessments) were rated the highest among educators.⁷

Educators also reported various experiences with ST, with most participants indicating some or no experience with ST.⁷ However, those who indicated they have experience with ST, did not know or specifically call it ST and most indicated they implemented ST by teaching chemistry concepts in context.⁷ While context-based learning can be used in a ST approach, ST approaches extend beyond putting concepts in context to engage learners in other ST skills.⁴⁷ Here, we communicated the need to clearly distinguish the requirements of a ST approach for both the instructor and learner and how to adapt current teaching approaches to incorporate these requirements for ST.⁷ Collectively, our research can guide priorities for educational change efforts on ST and alignment of these findings with other CER emphasizes the importance of addressing these challenges to achieve widespread ST implementation.

Considering these challenges, our second project focused on determining what educator barriers could be mitigated by understanding students' experiences with ST and where to place emphasis when teaching ST to students (Chapter 3). To know what to emphasize when teaching ST, we identified ST skills students readily demonstrate and other ST skills that need more explicit scaffolding in instruction.⁴⁸ However, assessment methods for ST skills are scarce in chemistry education, as emphasized by educators' perceived barriers on ST.^{7,49} During this time, our study was one of the first to develop a tool for assessing aspects of ST that encompasses multiple forms of assessment tasks including system maps, and written and verbal responses, which has not previously been shown in the literature.⁴⁸

ST activities and interviews with 26 undergraduate and graduate chemistry students showed that most students demonstrated the 11 ST skills that we assessed; however, some aspects of the ST skills

were demonstrated less frequently.⁴⁸ In particular, students' system maps (1) had fewer concepts and connections at submicroscopic levels of granularity (e.g., molecular, atomic, subatomic), (2) included multiple types of connections but limited circular loops and causal connections, and (3) demonstrated a breadth of connections but did not include connections in their system maps that considered human impact on chemistry.⁴⁸ Our findings suggest the need to be purposeful and explicit about the ST skills that are taught to students and the prompts and scaffolds used to elicit these skills.⁴⁸ This research is important for providing a starting point to understand how to assess ST skills in chemistry education which is required if ST is embedded into chemistry curricula.

The research in Chapter 4 builds on our understanding of students' experiences by more broadly exploring their experiences with the individual and collaborative ST tasks as well as identifying their perspectives.⁵⁰ Using the same study design and the remaining data collected from the 26 students from the research in Chapter 3, we found varying positive perspectives from students' engagement with the ST tasks and their perspectives of other students engaging with ST in a chemistry course.⁵⁰ Participants believed that ST: (1) is beneficial to learning, (2) captures interests and engagement, (3) allows perspectives to be shared and gained, and (4) provides personal, social, and professional relevance.⁵⁰

Students also had varying experiences related to constructing their system maps individually and collaboratively.⁵⁰ Students reported beneficial experiences which included, the appreciation of different perspectives and ideas from group members, group system map construction was more meaningful than their individual maps, and the group task helped them to identify more concepts and connections.⁵⁰

While most students reported positive and beneficial experiences, there were also some aspects of the ST tasks that students found challenging. Students reported difficulties with making connections, specifically to chemistry concepts, and indicated that time, their knowledge, and technology skills limited the construction of their individual and group system maps.⁵⁰ Aside from the opportunities and challenges of constructing system maps, we also found different ways students approached and organized their system maps suggesting the need to support students with system map instruction if they are given specific expectations.⁵⁰

These findings significantly contribute to the literature in two ways (1) identifying ways to effectively implement ST into chemistry courses to support the development of ST skills and (2) shedding light on the potential for collaborative ST approaches to improve diversity and inclusion when learning chemistry. This research was the first in the literature to identify the potential value of ST approaches for improving EDI as well as decolonized and Indigenous perspectives in chemistry education which requires more investigation.

The research presented in Chapter 2 to 4 on ST in chemistry education is amongst the first in the field, thus this work is only a start to providing evidence on ST approaches in chemistry and serves as the groundwork required for future research on ST. Much more research is needed to determine the impacts of ST to chemistry education.

With this goal in mind, we developed a new ST study to experimentally investigate the impact of using a ST approach to support the evaluation of scientific misinformation (Chapter 5). In this chapter, I propose ST's role in evaluating misinformation and provide a detailed overview of the literature on educational approaches for evaluating scientific information, research questions and goals of the study, theoretical frameworks used to explore the research questions, and a comprehensive study design and analysis plan used to investigate the research questions. This study may have profound impacts on helping address the misinformation crisis we are currently faced with and expand our knowledge on the impact of a ST approach in chemistry education.

In the latter part of my graduate degree, I focused on mobilizing some of our research findings into practice through the development of a ST framework (Chapter 6). This ST framework is a valuable resource for helping educators who would like to embed a ST approach into their chemistry courses but do not know where to start.⁵¹ Educators also have access to examples that were created using the framework to help them with the process of ST implementation.⁵¹ This work also helps to mitigate ST knowledge and contextual barriers that we identified in our previous research.⁷

There can be many challenges when conducting research, as I have described at the beginning of the chapters in this thesis but, there are also several limitations. While I have already outlined limitations specific to each project within each manuscript, here I will share my thoughts on a few overarching limitations of my PhD work. Before doing so, I want to emphasize that these limitations do not take away from the value of our work and with more time and resources, these limitations can be achieved. However, I believe there is more value in sharing significant findings with stakeholders after making difficult choices to accept certain limitations rather than holding back from trying to address all limitations in a study.

The ST intervention and interviews we created to explore students' perspectives and experiences helped us achieve a deep understanding of how students' approach, engage, and perceive ST tasks, but these findings are limited to one institution in Canada and students who willingly volunteered their time to participate in this study. Therefore, one overarching limitation of this work is that we do not know if students within a class setting (where the study is integrated within the class, minimizing bias) or at different institutions around the world have the same experiences and perspectives as the students who

participated in our ST study. With any qualitative study, a small sample size is beneficial for exploring the depth of a phenomenon but less beneficial for understanding its breadth, limiting the generalizability of its findings. Different experiences and perspectives can change the criteria and approaches for implementing ST in chemistry courses; therefore any claims about best practices for implementing ST must be considered with caution. As more research on ST is conducted by other chemistry education researchers, any alignment of findings with our work will improve generalizability.

Another overarching limitation of the work presented in this thesis is that we do not know if the ST framework and the implications of our ST research are feasible for educators. We have yet to explore the impact of this work on educators while considering their different roles and contexts, which requires forming collaborations with educators to understand how the implications to our research and use of the ST framework can be embedded effectively into their teaching practice. The same can be true for understanding the impact on students' learning, which will be described in more detail in the following future directions section.

The work I have led or been a part of my PhD on ST in chemistry education is amongst the first in the field and has significantly contributed to a better understanding of ST in chemistry education. From a different perspective, our work has further reached other areas of chemistry education including educational change, assessment, curricular development, and EDI. Our work on educators' perspectives has informed other research and initiatives such as the development of new frameworks for ST in chemistry education,^{52,53} and further investigation into educators' perspectives and beliefs of ST and new approaches (e.g., green chemistry).^{15,54–58} Findings from our research on the assessment of students' ST skills have been used to inform other research studies on ST skill assessment^{59,60} and are considered in the development of an educational framework.⁶¹ While it is too early to see the impact of our recent ST student perspectives and experiences research on the chemistry education communities, this work opens doors for new conversations and ideas about ST's potential impact on EDI in chemistry education, which is an emerging topic in the field.^{62–64} I believe there is a lot of potential for a ST approach in chemistry but much more investigation is required to understand its impacts on the field, and once this information is known and resources are provided (e.g., ST integration in textbooks, assessment questions and tools, incentives, administration support) then chemistry educators might be more willing to implement a ST approach in their courses. I am excited to see what the future looks like for ST in chemistry education.

7.2 Future research directions for systems thinking in chemistry education.

I communicate my perspectives on future research for ST in chemistry education by first reflecting on an article published on the future directions for ST in chemistry education in 2019. This article was published at the time I started my degree and serves as a great reflection of what the field has accomplished over the years and what has yet to be investigated. In this article, the authors communicate the need for evidence-based research on the effects and impacts of ST approaches and initiatives, with research areas on the cognitive domain, affective outcomes, long-term transfer of knowledge and skills, and EDI in chemistry.⁶⁵ Our research covers three of these areas – the cognitive domain, affective outcomes, and EDI. Other researchers have also completed cognitive studies focused on investigating how students engage with system maps or conceptual modelling in chemistry education,^{12,15,48,50,60,66,67} and the ST skills they demonstrate.^{48,60,67} Most of these studies, including our own, investigates how ST skills are demonstrated by engagement of chemistry concepts. To my knowledge, no studies have yet focused on the influence of ST approaches on students' understandings or reasoning of key chemistry concepts and ideas. Investigating this specific area of ST research will help to address the overarching need of identifying the impact of ST approaches on chemistry education.

There are still many research opportunities needed to explore affective outcomes and EDI in chemistry. About a handful of papers from the literature, including our work and others, have uncovered some potential affective implications of ST approaches in chemistry based on chemistry students' and educators' feedback and perspectives.^{7,12,15,44,45,50,55} These were all qualitative studies due to the goal of uncovering ideas to learn more about how students and educators perceive ST. The findings from these qualitatively studies can now be investigated more broadly, quantitatively. For example, experimental studies need to investigate if ST approaches (e.g., collaborative verses individual approaches) improve student engagement, self-efficacy beliefs, and attitudes toward chemistry compared to other teaching approaches. The same is recommended for EDI studies in chemistry. Now that we have uncovered the potential of collaborative ST approaches for improving EDI in chemistry, we need to measure the inclusion and equity outcomes of this approach (e.g., student retention and persistence in chemistry, disparities in academic success of underrepresented students). There has been more attention toward EDI studies in our field and across disciplines, making this avenue of research particularly valuable to the broader science community.

The last area of future ST research I will discuss is focused on the area that has not yet been published, long-term transfer of knowledge and skills in chemistry. Investigating the impacts of a ST approach on students' long-term knowledge and their ability to transfer chemistry reasoning and skills to

different contexts requires longitudinal studies.^{65,68} Ironically, when I communicate how a ST approach has been proposed to complement current teaching approach in my presentations and recent manuscript, I emphasize that a ST approach could aid in the transfer of knowledge and skills. Yet, we have no evidence of this proposed claim, partially because longitudinal studies require more time and resources, and we first need evidence to know how to effectively implement ST into chemistry courses and into the curriculum. To date, the qualitative ST studies and efforts for implementing ST into the chemistry curriculum open more possibilities for investigating the transfer of knowledge and skills when using a ST approach. Ideally, these studies would be conducted in a chemistry course that embed ST learning outcomes into the chemistry curriculum. Students' knowledge and skills can then be measured through assessment tasks at several time points in the course. Long-term, if ST is made a requirement in chemistry programs, then students' transfer of knowledge and skills can be measured across courses over several years. These longitudinal studies would complement cognitive studies on students' understanding of chemistry concepts and together they will produce more evidence on the impacts of ST in chemistry education.

We still have a long journey with ST research in chemistry education as we have yet to have a comprehensive understanding of the impacts of ST approaches to the field. Despite this, I am proud of the contributions I have made to chemistry education research, as this work can spearhead new learnings, initiatives, and much-needed future research on ST in chemistry education. I am excited to see where and how the chemistry education community continues this journey of investigating ST and I hope my work inspires new leaders in the field to get involved.

7.3 Final remarks of PhD thesis

Throughout my degree, I have worn many hats and have experienced many positive and negative life events, and through these different roles and experiences, I have grown professionally and personally. To give some context, I have always struggled with my self-worth and self-confidence – attending graduate school, let alone a PhD, was something I did not believe I could do or achieve. I worked a lot on challenging this belief throughout my degree, but I also had incredible mentors who provided me with opportunities that showed me what I could achieve, taught me new skills, and supported me on my journey.⁶⁹ Progress reports are one of the tasks Dr. Flynn assigns group members to complete at the end of each semester and included in this task, we are asked to write personal reflections. Not only have these progress reports made it easier to write this thesis, but they provide evidence of my professional and personal growth, and my ability to complete this PhD.

In this last part of my thesis, I share some of the reflections I have completed along the way to communicate how my academic and personal experiences and more importantly, the influence of amazing mentorship has helped me grow and overcome the belief of not being able to complete this PhD.

Starting graduate school was difficult not only from starting a new role and settling in a new environment but also due to navigating personal and global circumstances. I had a sick family member who was very close to me, and I would travel back and forth to visit them. Often, due to the travels, I would miss out on graduate student social events. The combination of these events made me constantly feel behind and overwhelmed academically and socially in graduate school. Dr. Flynn understood the challenges I was faced with and showed patience and support by not putting additional expectations on me and giving me the time and space to deal with these challenges.

I knew I made the right decision to join the Flynn Research Group when Dr. Flynn acknowledged my values and personal and professional goals, and she has continued to support me with these goals throughout my PhD. I was also allowed to make decisions and take ownership of the design of ST studies which, gave me a sense of agency, boosted my confidence, and made me feel invested in my research. One-on-one weekly meetings with Dr. Flynn as well as group meetings with our collaborator, Dr. Peter Mahaffy, helped to define short- and long-term goals for our ST project and they provided constructive feedback and questions to help advance the project. When I finally felt I was making substantial progress on my research, the world was shut down by the COVID-19 pandemic.

Most of my graduate degree was completed during the COVID-19 pandemic, which created many negative but also positive experiences. The isolating nature of the pandemic made it challenging to create new friendships and discover where I fit in graduate school. Conferences were cancelled and offered online. While it was a privilege to have the opportunity to attend these online conferences, networking was limited, which is a primary benefit of conferences. Along with other graduate students, the pandemic impacted productivity and forced me to redesign aspects of the study to collect data virtually. This experience was the first of many where Dr. Flynn played a critical role in supporting me to navigate research challenges and develop resilience.

Dr. Flynn provided me with opportunities that helped me witness and develop confidence in my academic abilities. She sees the value of bringing students to the table to tackle educational challenges and build resources. Therefore, she invited our graduate chemistry education research class to contribute to the development of an eBook on Remote Teaching: A Guide for Teaching Assistants.⁷⁰ This book is an Open Educational Resource designed to provide teaching assistants from all five departments

in the Faculty of Science with teaching approaches and strategies to transition to a remote teaching environment. With the uncertainty of what remote teaching could look like, this book provided and continues to provide teaching assistants (TAs) with many resources to ease the stress for transitioning to remote teaching; for some, a very unfamiliar approach. I was one of two graduate students who contributed to this eBook as a co-author, and I was able to share my experiences teaching in both secondary and post-secondary education. Dr. Flynn further provided me the opportunity to develop synchronous workshops to help TAs practice the skills and teaching approaches that are explained in the book.

After experiencing so much isolation from the pandemic, 2022 was a huge turning point in my academic career and personal life. There was so much to look forward to when life started coming back to “normal”. The 2022 Canadian Chemistry Conference and Exhibition was my first in-person National conference, and I remember the excitement of meeting so many well-known, established scholars in Chemistry Education. This was the start of making many long-lasting connections in the chemistry education communities and these connections are one of the things I cherish the most from my PhD. Over the years, Dr. Flynn has taught me valuable skills for giving presentations at these conferences and I have become more confident with my ability to present my work due to her support and guidance.

While I experienced many memorable events and opportunities in 2022 including attending in person conferences, submitting a manuscript, in-person learning and teaching, getting married, and honeymooning in Africa, these were all very big events, and I did not give myself a break to process it all nor reset for the new school year leading to a mental health crisis. I got beyond the point of exhaustion, feeling like I could not keep up with my research or personal life, which led to a downwards spiral of my mental and physical states. This was a scary time of my life and there were moments where I felt I could not continue pursuing this degree, but I was able to overcome this challenge with the help of my incredible support system— my husband, my family, Dr. Flynn, and the University of Ottawa Health and Wellness Centre.

I share this personal information in my thesis not to receive sympathy but to help reduce the stigma surrounding mental health in the academic community and emphasize the important role of supervisors’ support in these situations. Over recent years, issues related to mental health and well-being in academia have attracted increasing attention from researchers and the media.⁷¹ However, mental health or feelings of imposter syndrome are often not talked about in academic settings. As exemplified by a mental health advocate, Dr. Zoe Ayres, who is the founder of Voices of Academia,⁷² and author of the book *Managing your mental health during your PhD*,⁷³ sharing mental health and wellness stories can

help to promote mental health in education and work towards a culture where wellness is acknowledged as a critical part of being a successful academic and professional.

I am super fortunate to have a supervisor who values mental health and supported me by giving me the time and space to focus on my well-being. I realize not everyone in academia is provided with that same level of support, so I urge the academic community to treat one another with kindness and to learn more about mental health and ways to be an ally. Doing so may help one develop the resilience to overcome challenges, like it did for me just before my final year of my degree.

This last year has been the most impactful, memorable, and rewarding as a researcher, professional, and person as I have been privileged with many opportunities that allowed me to share my research more broadly. Most of these opportunities came from my involvement with the IUPAC Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond project.⁷⁴ I deeply thank Dr. Peter Mahaffy for the invitation and the rest of the working group members for welcoming me into the project. While it was first intimidating to work with so many esteemed scholars, being a member of this working group made me feel that my research and expertise was valued and that I could make a greater contribution to the chemistry and chemistry education communities. Additionally, I gained more experience with collaboration leading to a manuscript and co-leading a workshop on systems thinking at the International Conference on Chemistry Education in Thailand. At this conference, I met international chemistry educators who told me they were thrilled to meet me as they have been following my work closely over the years. One my lifelong goals is to make a positive impact, so knowing my work has been beneficial to people internationally brings me great joy and fulfillment.

As I reflect on this journey, I am incredibly thankful for all these opportunities given to me that have helped me grow professionally and personally. The challenging experiences played a significant contribution to this growth and resilience. I believe there are overarching lessons to learn and take away from every experience.

In these last few words, I will share some final advice for fellow graduate students based on what I learned from my experiences during my PhD. Find mentors and engage with people who will push you and give you opportunities to see your fullest potential, lift you up instead of bringing you down, teach you professional skills beyond just those related to graduate school or academia, and who will support and respect your values and goals. Without my incredible mentors, Dr. Alison Flynn and Dr. Peter Mahaffy, who taught me new skills and supported me on my journey, I am not sure I would have been here writing this thesis. I now feel empowered to take on the next chapter of my life. For those who are starting or are on this journey, you got this!

7.4 References

- (1) Colberg, J.; Kuok (Mimi) Hii, K.; Koenig, S. G. Importance of Green and Sustainable Chemistry in the Chemical Industry: A Joint Virtual Issue between *ACS Sustainable Chemistry & Engineering* and *Organic Process Research & Development*. *Org. Process Res. Dev.* **2022**, 26 (8), 2176–2178. <https://doi.org/10.1021/acs.oprd.2c00171>.
- (2) MacDonald, R. P.; Pattison, A. N.; Cornell, S. E.; Elgersma, A. K.; Greidanus, S. N.; Visser, S. N.; Hoffman, M.; Mahaffy, P. G. An Interactive Planetary Boundaries Systems Thinking Learning Tool to Integrate Sustainability into the Chemistry Curriculum. *J. Chem. Educ.* **2022**, 99 (10), 3530–3539. <https://doi.org/10.1021/acs.jchemed.2c00659>.
- (3) Chemistry Education Needs a Green Reset. *Nature* **2022**, 604 (598). <https://doi.org/10.1038/d41586-022-01109-z>.
- (4) Holme, T. Considering Big Questions via Chemistry Education Summits. *J. Chem. Educ.* **2024**, 101 (1), 1–2. <https://doi.org/10.1021/acs.jchemed.3c01297>.
- (5) ACS Green Chemistry Institute. *Chemistry Education Summit: Reimagining Chemistry Education*. <https://www.acs.org/sustainability/summits/education.html> (accessed 2024-03-15).
- (6) Whalen, J. M.; Matlin, S. A.; Holme, T. A.; Stewart, J. J.; Mahaffy, P. G. *Transforming the Science of Transformation toward Sustainability: The Case of Ammonia and Reactive Nitrogen*; preprint; Chemistry, 2022. <https://doi.org/10.26434/chemrxiv-2022-nwk6n>.
- (7) 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**, 99 (7), 2474–2483. <https://doi.org/10.1021/acs.jchemed.2c00138>.
- (8) 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>.
- (9) 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>.
- (10) Wissinger, J. E.; Visa, A.; Saha, B. B.; Matlin, S. A.; Mahaffy, P. G.; Kümmerer, K.; Cornell, S. Integrating Sustainability into Learning in Chemistry. *J. Chem. Educ.* **2021**, 98 (4), 1061–1063. <https://doi.org/10.1021/acs.jchemed.1c00284>.

- (11) Aubrecht, K. B.; Bourgeois, M.; Brush, E. J.; MacKellar, J.; Wissinger, J. E. Integrating Green Chemistry in the Curriculum: Building Student Skills in Systems Thinking, Safety, and Sustainability. *J. Chem. Educ.* **2019**, *96* (12), 2872–2880. <https://doi.org/10.1021/acs.jchemed.9b00354>.
- (12) Eaton, A. C.; Delaney, S.; Schultz, M. Situating Sustainable Development within Secondary Chemistry Education via Systems Thinking: A Depth Study Approach. *J. Chem. Educ.* **2019**, *96* (12), 2968–2974. <https://doi.org/10.1021/acs.jchemed.9b00266>.
- (13) 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>.
- (14) 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>.
- (15) 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>.
- (16) Mahaffy, P. G.; Ho, F. M.; Haack, J. A.; Brush, E. J. Can Chemistry Be a Central Science without Systems Thinking? *J. Chem. Educ.* **2019**, *96* (12), 2679–2681. <https://doi.org/10.1021/acs.jchemed.9b00991>.
- (17) 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>.
- (18) Assaraf, O. B.; Orion, N. System Thinking Skills at the Elementary School Level. *J. Res. Sci. Teach.* **2010**, *47* (5), 540–563. <https://doi.org/10.1002/tea.20351>.
- (19) Verhoeff, R. P. Towards Systems Thinking in Cell Biology Education, Centrum voor Didactiek van Wiskunde en Natuurwetenschappen, Universiteit Utrecht, Utrecht, 2003.
- (20) 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>.
- (21) Hmelo-Silver, C. E.; Pfeffer, M. G. Comparing Expert and Novice Understanding of a Complex System from the Perspective of Structures, Behaviors, and Functions. *Cogn. Sci.* **2004**, *28* (1), 127–138. https://doi.org/10.1207/s15516709cog2801_7.

- (22) 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>.
- (23) 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>3.0.CO;2-T](https://doi.org/10.1002/1520-6858(200033)3:3<163::AID-SYS5>3.0.CO;2-T).
- (24) Zaraza, R. Systems Thinking in the Classroom. 9.
- (25) Sweeney, L. B. *How Is This Similar to That? The Skill of Recognizing Parallel Dynamic Structures on Center Stage*. Creative Learning Exchange [Online]. <http://static.clexchange.org/ftp/documents/Research/RS2005-09Homology.pdf> (accessed 2021-07-29).
- (26) Forrester, J. W. System Dynamics as an Organizing Framework for Pre-college Education. *Syst. Dyn. Rev.* **1993**, *9* (2), 183–194. <https://doi.org/10.1002/sdr.4260090207>.
- (27) Draper, F.; Swanson, M. Learner-Directed Systems Education: A Successful Example. *Syst. Dyn. Rev.* **1990**, *6* (2), 209–213. <https://doi.org/10.1002/sdr.4260060206>.
- (28) Lyneis, D. A. BRINGING SYSTEM DYNAMICS TO A SCHOOL NEAR YOU Suggestions for Introducing and Sustaining System Dynamics In. **2001**, 16.
- (29) Richmond, B. Systems Thinking: Critical Thinking Skills for the 1990s and Beyond. *Syst. Dyn. Rev.* **1993**, *9* (2), 113–133. <https://doi.org/10.1002/sdr.4260090203>.
- (30) Fisher, D. M. “Everybody Thinking Differently”: K-12 Is a Leverage Point: Everybody Thinking Differently: K-12 Is a Leverage Point. *Syst. Dyn. Rev.* **2011**, *27* (4), 394–411. <https://doi.org/10.1002/sdr.473>.
- (31) Sabelli, N. H. Complexity, Technology, Science, and Education. *J. Learn. Sci.* **2006**, *15* (1), 5–9. https://doi.org/10.1207/s15327809jls1501_3.
- (32) Yoon, S. A.; Goh, S. E.; Park, M. Teaching and Learning About Complex Systems in K–12 Science Education: A Review of Empirical Studies 1995–2015. *Rev. Educ. Res.* **2018**, *88* (2), 285–325. <https://doi.org/10.3102/0034654317746090>.
- (33) 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>.
- (34) Goldstone, R. L.; Wilensky, U. Promoting Transfer by Grounding Complex Systems Principles. *J. Learn. Sci.* **2008**, *17* (4), 465–516. <https://doi.org/10.1080/10508400802394898>.
- (35) Jacobson, M. J.; Wilensky, U. Complex Systems in Education: Scientific and Educational Importance and Implications for the Learning Sciences. *J. Learn. Sci.* **2006**, *15* (1), 11–34.

- (36) 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>.
- (37) Arnold, R. D.; Wade, J. P. A Definition of Systems Thinking: A Systems Approach. *Procedia Comput. Sci.* **2015**, *44*, 669–678. <https://doi.org/10.1016/j.procs.2015.03.050>.
- (38) Booth Sweeney, L. Learning to Connect the Dots: Developing Children’s Systems Literacy. *Solutions* **2012**, *5* (3), 55–62.
- (39) Caulfield, C. W.; Maj, S. P. A Case for Systems Thinking and System Dynamics. In *2001 IEEE International Conference on Systems, Man and Cybernetics. e-Systems and e-Man for Cybernetics in Cyberspace (Cat.No.01CH37236)*; IEEE: Tucson, AZ, USA, 2001; Vol. 5, pp 2793–2798. <https://doi.org/10.1109/ICSMC.2001.971932>.
- (40) Cloud, J. P. Some Systems Thinking Concepts for Environmental Educators during the Decade of Education for Sustainable Development. *Appl. Environ. Educ. Commun.* **2005**, *4* (3), 225–228. <https://doi.org/10.1080/15330150591004625>.
- (41) Forrester, J. W. Learning through System Dynamics as Preparation for the 21st Century. *Syst. Dyn. Rev.* **2016**, *32* (3–4), 187–203. <https://doi.org/10.1002/sdr.1571>.
- (42) Jacobson, M. J. Complex Systems and Learning: Empirical Research, Issues, and “Seeing” Scientific Knowledge with New Eyes. 9.
- (43) 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>.
- (44) 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>.
- (45) Delaney, S.; Ferguson, J. P.; Schultz, M. Exploring Opportunities to Incorporate Systems Thinking into Secondary and Tertiary Chemistry Education through Practitioner Perspectives. *Int. J. Sci. Educ.* **2021**, *43* (16), 2618–2639. <https://doi.org/10.1080/09500693.2021.1980631>.
- (46) 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>.

- (47) 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>.
- (48) 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.* **2023**, *100* (5), 1763–1776. <https://doi.org/10.1021/acs.jchemed.2c00955>.
- (49) Talanquer, V. Some Insights into Assessing Chemical Systems Thinking. *J. Chem. Educ.* **2019**, *96* (12), 2918–2925. <https://doi.org/10.1021/acs.jchemed.9b00218>.
- (50) Szozda, A. R.; Lalani, Z.; Behrooz, S.; Mahaffy, P. G.; Flynn, A. B. "Systems Thinking (ST) Encourages a Safe Space to Offer Different Perspectives and Insights": Student Perspectives and Experiences with ST Activities. *J. Chem. Educ.* **2024**, *101* (6), 2290–2307. <https://doi.org/10.1021/acs.jchemed.4c00080>.
- (51) Talanquer, V.; Szozda, A. R. An Educational Framework for Teaching Chemistry Using a Systems Thinking Approach. *J. Chem. Educ.* **2024**, *101* (5), 1785–1792. <https://doi.org/10.1021/acs.jchemed.4c00216>.
- (52) Ridley, A. J.; Wentzel, M. T.; Dugmore, T. I. J.; Hurst, G. A. Using a Temporal Systems Thinking Framework to Design and Redesign a Biorefinery. *J. Chem. Educ.* **2024**, *101* (3), 1379–1386. <https://doi.org/10.1021/acs.jchemed.3c01126>.
- (53) Tümay, H. Systems Thinking in Chemistry and Chemical Education: A Framework for Meaningful Conceptual Learning and Competence in Chemistry. *J. Chem. Educ.* **2023**, *acs.jchemed.3c00474*. <https://doi.org/10.1021/acs.jchemed.3c00474>.
- (54) Idul, J. J. A.; Walag, A. M. P. Integrating Green Chemistry and Sustainability Principles to a Secondary Science Curriculum: A Mixed-Methods Needs Assessment. *J. Chem. Educ.* **2024**, *acs.jchemed.4c00341*. <https://doi.org/10.1021/acs.jchemed.4c00341>.
- (55) York, S.; Orgill, M. Experienced Tertiary Instructors' Perceptions of the Benefits and Challenges of Systems Thinking in Chemistry Education. *J. Chem. Educ.* **2024**, *101* (1), 10–23. <https://doi.org/10.1021/acs.jchemed.3c01000>.
- (56) Parker, A.; Noronha, E.; Bongers, A. Beyond the Deficit Model: Organic Chemistry Educators' Beliefs and Practices about Teaching Green and Sustainable Chemistry. *J. Chem. Educ.* **2023**, *100* (5), 1728–1738. <https://doi.org/10.1021/acs.jchemed.2c00780>.

- (57) Peretz, R.; Tal, M.; Akiri, E.; Dori, D.; Dori, Y. J. Fostering Engineering and Science Students' and Teachers' Systems Thinking and Conceptual Modeling Skills. *Instr. Sci.* **2023**, *51* (3), 509–543. <https://doi.org/10.1007/s11251-023-09625-9>.
- (58) Grieger, K.; Hill, B.; Leontyev, A. Exploring Curriculum Adoption of Green and Sustainable Chemistry in Undergraduate Organic Chemistry Courses: Results from a National Survey in the United States. *Green Chem.* **2022**, *24* (22), 8770–8782. <https://doi.org/10.1039/D2GC02999E>.
- (59) Liang, Y.; Xiao, Z.; Wang, S.; Li, Y.; Li, H. An Interdisciplinary Practical Project for Preservice Science Teachers: Visualizing Climate Change Based on Systems Thinking. *J. Chem. Educ.* **2024**, acs.jchemed.3c01271. <https://doi.org/10.1021/acs.jchemed.3c01271>.
- (60) Reynders, M.; Pilcher, L. A.; Potgieter, M. Teaching and Assessing Systems Thinking in First-Year Chemistry. *J. Chem. Educ.* **2023**, *100* (3), 1357–1365. <https://doi.org/10.1021/acs.jchemed.2c00891>.
- (61) Day, E. L.; Petritis, S. J.; McFall-Boegeman, H.; Starkie, J.; Zhang, M.; Cooper, M. M. A Framework for the Integration of Green and Sustainable Chemistry into the Undergraduate Curriculum: Greening Our Practice with Scientific and Engineering Practices. *J. Chem. Educ.* **2024**, acs.jchemed.3c00737. <https://doi.org/10.1021/acs.jchemed.3c00737>.
- (62) Deng, J. M.; McMunn, L. E.; Oakley, M. S.; Dang, H. T.; Rodriguez, R. S. Toward Sustained Cultural Change through Chemistry Graduate Student Diversity, Equity, and Inclusion Communities. *J. Chem. Educ.* **2021**, acs.jchemed.1c00485. <https://doi.org/10.1021/acs.jchemed.1c00485>.
- (63) Ryu, M.; Bano, R.; Wu, Q. Where Does CER Stand on Diversity, Equity, and Inclusion? Insights from a Literature Review. *J. Chem. Educ.* **2021**, *98* (12), 3621–3632. <https://doi.org/10.1021/acs.jchemed.1c00613>.
- (64) 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>.
- (65) 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>.
- (66) Krab-Hüsken, L. E.; Pei, L.; De Vries, P. G.; Lindhoud, S.; Paulusse, J. M. J.; Jonkheijm, P.; Wong, A. S. Y. Conceptual Modeling Enables Systems Thinking in Sustainable Chemistry and Chemical Engineering. *J. Chem. Educ.* **2023**, *100* (12), 4577–4584. <https://doi.org/10.1021/acs.jchemed.3c00337>.

- (67) Vachliotis, T.; Salta, K.; Tzougraki, C. Developing Basic Systems Thinking Skills for Deeper Understanding of Chemistry Concepts in High School Students. *Think. Ski. Creat.* **2021**, *41*, 100881. <https://doi.org/10.1016/j.tsc.2021.100881>.
- (68) National Research Council. *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*; National Academies Press: Washington, D.C., 2012; p 13362. <https://doi.org/10.17226/13362>.
- (69) Deng, J. M.; Ahmed, S. E.; Awoonor-Williams, E.; Banerjee, P.; Barecka, M. H.; Bickerton, L. E.; Di Pietro, S. A.; Dorn, S. K.; Jablonka, K. M.; Laudadio, G.; Kreidt, E.; Mannocho-Russo, H.; Terra, J.; Wilkins, O. H.; Yerneni, S. S.; Yusuf, M. Prioritizing Mentorship as Scientific Leaders. *ACS Cent. Sci.* **2024**, *10* (2), 209–213. <https://doi.org/10.1021/acscentsci.3c00500>.
- (70) Allen, M.; Szozda, A. R.; Kerr, J.; Flynn, A. B. *Remote Teaching: A Guide for Teaching Assistants*; eCampusOntario: University of Ottawa; Ottawa, ON.
- (71) Shaw, C.; Ward, L. *Dark thoughts: why mental illness is on the rise in academia*. <https://www.theguardian.com/higher-education-network/2014/mar/06/mental-health-academics-growing-problem-pressure-university>.
- (72) Ayres, Z. J. *Voices of Academia*. <https://voicesofacademia.com/2020/06/01/why-your-voice-matters-welcome-to-voices-of-academia/>.
- (73) Ayres, Z. J. *Managing Your Mental Health during Your PhD: A Survival Guide*; Springer International Publishing: Cham, 2022. <https://doi.org/10.1007/978-3-031-14194-2>.
- (74) IUPAC Systems Thinking in Chemistry for Sustainability: 2030 and Beyond (STCS 2030+) project. *Systems Thinking in Chemistry Education*. <https://sites.google.com/view/sastice/home> (accessed 2024-07-08).

Chapter 8: Appendices

8.1 Appendix 1: Supporting Information for Chapter 2

Supporting Information: Investigating educators' perspectives towards systems thinking in chemistry education from international contexts

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8.1.1 SI for Methods

8.1.1.1 Instrument for data collection

All questions in part 1 of the questionnaire used a 5-point Likert scale followed by “please provide an explanation to your response.” The explanation was purposefully implemented into the questionnaire to obtain response-process validity and to help distinguish the difference between the descriptive items on the Likert scale. Likert scale questions designed for the student and educator aimed to determine the extent of each barrier currently present in the literature and included the option “unsure”. We included this option because respondents may use the midpoint value in a Likert scale as a ‘dumping ground’ when they are responding to survey items that are unfamiliar to them, ambiguous, or socially undesirable.⁴

8.1.1.2 Validity Evidence

We aimed to establish validity of the data through three approaches: content validation methods, trustworthiness, and peer debriefing.⁵⁻⁷ Content validation methods were performed to assess the quality of responses to items in the questionnaire. Here, two experts who research STICE completed the educator questionnaire and provided comments to improve items. Changes to items were made accordingly. We strove to maximize the trustworthiness of our results by providing the questionnaire in the SI and providing detailed descriptions of our

participants and analysis methods. We also gave participants opportunities to explain their responses to the Likert scale questions in the questionnaire. These open-ended response items allowed participants to communicate any positive or negative beliefs and perspectives they had about the ST approach. Lastly, peer debriefing was used throughout the duration of the study. Regular sessions between the researchers and members of the Flynn Research Group allowed in-depth questions to be asked about the methods and interpretations and helped to address any assumptions and/or biases present in the analysis. This process maximized the credibility of the results.⁵

8.1.2 Participants

The online educator questionnaire was sent out internationally: as an email list submission and social media posts (*i.e.*, Twitter and Facebook). Furthermore, the questionnaire was provided in French and English to broaden the recruitment of participants.

Specifically, the questionnaire was sent out internationally to the Chemistry Education Division – Chemical Institute of Canada mail list, the Chemical Education Research mail list provided by Chemical Education Xchange and the Chemical Education Research committee of the Division of Chemical Education, Inc. of the American Chemical Society. Additionally, the questionnaire was sent through chemistry divisions of the American Chemical Society listservs to have a more diverse population (educators not limited to chemistry education research).

Table S1 shows the diversity of chemistry educators who participated in this study.

Table S1. Demographic information from the educator questionnaire.

Population Groups		Years of Teaching		Gender	
African	1	0 to 5	11	Woman	28
Australian	1	6 to 10	8	Man	24
Black	4	11 to 15	8	Non-binary	2
Chinese	1	16 to 20	9		
Japanese	1	21 to 25	9		
Latin American	1	26 to 30	4		
South Asian (<i>e.g.</i> , East Indian, Pakistani, Sri Lankan)	3	>30	6		
White	40				

Educator role		Courses taught by educators		Country of Institution	
Adjunct Professor	1	Analytical Chemistry	5	Australia	5
Assistant Professor	4	Biochemistry	3	Canada	20
Associate Professor	10	Bioorganic/Bioinorganic chem.	6	England	1
Full Professor	9	Chemistry Laboratory courses	1	Ghana	1
Lecturer or Instructor	10	Environmental chemistry	5	India	1
Professor Emeritus	1	Highschool chemistry	6	Mexico	1
Senior Instructor	5	Inorganic chemistry	8	Nigeria	1
Teacher (grades 9 to 12)	5	Introductory/General chemistry	35	South Africa	2
Teaching Assistants	2	Organic chemistry	20	United States	20
Other (<i>e.g.</i> , visiting faculty, course manager, undergraduate and graduate student)	9	Other Advanced chemistry (3 rd /4 th year)	7	Zimbabwe	
		Physical chemistry	3		
		Postgraduate chemistry	3		

Note: Descriptors were used from a combination of sources, including Canada's Natural Sciences and Engineering Research Council and Statistics Canada.

8.1.3 Data Analysis

While it is beneficial to detect educator perspectives via constant comparative analysis, additional use of quantitative methods can help enrich the evidence and answer the research question to the next level. Quantitative analysis was carried out for the Likert scale questions on knowledge, flexibility, and willingness to implement STICE as well as years of teaching experience, experience with STICE and the student and educator/educational barriers questions. To determine any relationships among the following factors: knowledge, flexibility, willingness to implement STICE, experience with STICE, and years of teaching experience, a Spearman's rank correlation test was conducted in SPSS.¹³ The correlation matrix of this test is provided in Table S3 along with effect sizes. Additionally, descriptive statistics are presented for educator's willingness to implement STICE, knowledge of STICE, experience with STICE, and flexibility of new teaching approaches (Table S4).

To assess the extent of student and educator/educational barriers perceived by participants, descriptive statistics (N, mean, standard deviation) of each barrier was computed by SPSS by removing the “unsure” responses from each barrier. The Likert scale labels for each question were transcribed to numeric labels to compute the calculation (*i.e.*, 1 – not at all a barrier, 5 – a complete barrier).

Kruskal Wallis tests were then conducted to see if there was a statistically significant difference in the average extent of barrier between the experience groups (Figure S8 and Figure S9)

8.1.4 Supplementary Theme 1: Knowledge, Experience, beliefs, Personal and contextual factors influence educators’ willingness to implement STICE

8.1.4.1 Themes for qualitative analysis

Table S2. Code book for educators' responses to their willingness to implement STICE.

Themes	Categories	Description	Representative quotes
Educators’ knowledge hinders educators’ willingness to implement	Educators’ need to gain more knowledge on STICE before deciding to implement	Mention they would consider implementing if they had more knowledge or guidance about ST and/or how to implement. Mention they do not know what ST is and would need to learn more.	“I understand the importance of STICE, but I am not sure how to implement it.” “Seeing that I don't know what ST is, I can't really say whether I would implement it, but I am open to consideration.”
Educators’ beliefs support educators’ willingness to implement	Educators believe ST helps with student skill, knowledge development, and engagement for learning chemistry Note: student engagement beliefs come from importance to implement STICE question in part 2 of the questionnaire and do not overlap with the beliefs in the	Educators’ mention: ST aids student understanding of chemistry concepts and its relevance to other contexts/disciplines. ST aids students with high level thinking skill development. ST increases student engagement for learning chemistry.	“I love the idea of ST and trying to implement it also. It enables students to understand concepts better and see their practical application.” “I think it will increase student engagement, give non-majors a greater appreciation for chemistry and improve students' scientific knowledge and, potentially, their scientific communication skills.”

	willingness to implement question in part 1 of the questionnaire		
	Educators believe ST is important for the future of chemistry	Educators' mention: ST allows chemistry to be viewed from multiple perspectives due to its connections to other disciplines/contexts. This way of thinking will benefit society and future scientists by thinking holistically about the consequences of actions. Helps provide structure or modernize the curriculum.	"I believe implementing a ST approach can complement what students are learning in their courses, including linking course work to other courses." "I believe we need to apply this to make the science more responsible for not just what we discover/produce but how that affects the world and sustainability rather than the quick fix."
Experience with STICE supports educators' willingness to implement	Educators are planning to implement or have already implemented STICE	Educators' mention: They are already planning to implement ST into their course(s). They have already implemented a ST approach.	"We are in the process of designing a new curriculum for the laboratory. I have been asked to come up with a proposal. I have already mentioned that trending topics like ST should be a part of our curriculum."
Personal factors hinder and support educators' willingness to implement	Educators are interested in learning new approaches	Educators' mention: They are interested in learning and trying new approaches.	"I am interested in adopting the STICE approach."
	Educators are willing to try new approaches	Educators' mention: They are always willing to give new approaches a try.	"Since I am able to incorporate learning activities in my classes, I am always looking for new ones to incorporate."
	Approach needs to align with teaching values or current approach	Educators' mention: They are likely to integrate ST if it aligns with their values or current approach.	"If it's close to my current thinking, then more likely to adopt it and integrate it. If it's far afield, less likely."
Contextual factors hinder educators' willingness to implement	Need for available resources	Educators' mention: They need resources that are available and easy to use, understand and implement. Might implement if approach meets course learning outcomes/allows content to be covered.	"If resources were readily available, I would consider integrating STICE into each of my courses." "I am not likely to integrate fully developed materials into my courses because I have very
	Concerns about curriculum coverage		

	Research-based evidence needs to be considered before implementing	Need to be convinced that it is an effective approach and/or beneficial for students. Need time to learn and/or integrate STICE into course or curriculum.	specific learning objectives to achieve.” “I would do my best to do it if I am convinced of its benefits.” “I don't have much time, and I can only do so much to develop or change my course as a result.”
	Need time to learn and/or integrate STICE		

8.1.4.2 Results from Quantitative Analysis

Table S3. Spearman's rank correlation table of five factors from the educator questionnaire

	Flexibility	Knowledge	Willingness	Years of Teaching	Experience with STICE
Flexibility	1.000	-0.140 [-.402, .115]	-0.171 [-.435, .096]	0.328* [.029, .578]	0.129 [-.131, .356]
Knowledge	-0.140 [-.402, .115]	1.000	0.457** [.184, .674]	-0.034 [-.334, .269]	0.264 [-.010, .537]
Willingness	-0.171 [-.435, .096]	0.457** [.184, .674]	1.000	0.018 [-.323, .351]	0.184 [-.142, .500]
Years of Teaching	0.328* [.029, .578]	-0.034 [-.334, .269]	0.018 [-.323, .351]	1.000	0.086 [-.224, .366]
Experience	0.129 [-.131, .356]	0.264 [-.010, .537]	0.184 [-.142, .500]	0.086 [-.224, .366]	1.000

** . Correlation is significant at the 0.01 level (2-tailed)

* . Correlation is significant at the 0.05 level (2-tailed)

Bias corrected accelerated 95% confidence intervals are provided in brackets.

Effect size of r_s based on Cohen (1992): small = 0.1; medium = 0.3; large = 0.5

Quantitative analysis showed there were only two significant relationships between factors with a medium effect size: (1) knowledge on STICE correlates with educators' willingness to implement STICE and (2) the number of years an educator teaches correlates with educators' flexibility to adopt new teaching approaches.

Table S4. Descriptive statistics of the five factors from the educator questionnaire

<i>Likert scale questions from educator questionnaire</i>	Mean	95% Confidence Interval for mean		Std. Deviation	N
		Lower	Upper		
<i>Willingness to implement STICE</i>	3.44	3.19	3.70	0.641	55
<i>Knowledge on STICE</i>	2.52	2.12	2.92	1.014	55
<i>Experience with STICE</i>	1.74	1.51	1.98	0.594	55
<i>Years of teaching experience</i>	3.37	2.53	4.21	2.115	54
<i>Flexibility with new teaching approaches</i>	3.70	3.34	4.06	0.912	56

8.1.4.3 Contextual Factors

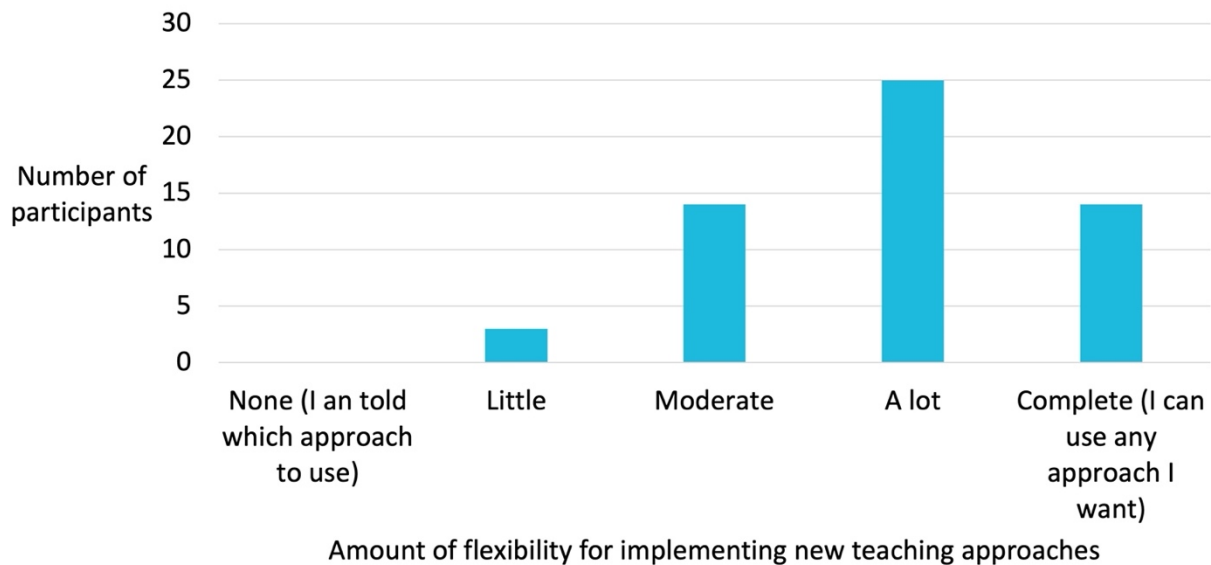


Figure S1. Educators' perceived flexibility for implementing new teaching approaches (N = 56).

In the questionnaire, participants were also asked to identify and explain their level of flexibility for implementing new teaching approaches. While participants generally reported to have a high level of flexibility (Figure S1), the same four contextual factors (*i.e.*, availability of teaching resources, curriculum coverage, research-based evidence, and time constraints to learn and implement STICE) identified in the manuscript (Figure 3), emerged from thematic analysis. Based on the TCSR model (Figure 1), these four factors can be categorized as broader culture contextual factors (n = 31) and align with the educator and educational barriers of

STICE that are present in the literature. Additional contextual factors related to institutional context and culture (n = 20) and department and subject area context (n = 14) were also identified from educator's flexibility responses (Table S5).

It is not surprising that institutional context and culture was the second most significant factor that hindered and allowed participants to have flexibility to try new approaches as institutional size, policy, and expectations are not consistent amongst institutions and high school educators have vastly different experiences and working contexts than post-secondary educators.

Table S5. Code book for educators' responses for flexibility of new teaching approaches.

Themes	Categories	Description	Representative quotes
Broader cultural context restricts and allows freedom of approach used	Resource usage is restriction for flexibility	Mentioned the following factors restrict flexibility: Lack of resource support. Requirement to meet course objectives/content/curriculum. Lack of evidence to support this approach. Time required to implement approach.	"In addition, research needs to be prioritized - also a factor in considering the time cost." "I am very much constrained by what curriculum I am supposed to cover." "The only main obstacle is the amount of lecture time I have to effectively cover course content."
	Constrained by curriculum, course content, syllabus, and learning objectives		
	Evidence of approach needs to be considered		
	Time for learning and implementing restricts ability to implement		
	Freedom to use any approach they want	Explicitly mentioned that they have complete flexibility to use any approach they want.	"Nobody has ever suggested how I should teach anything!"
Institutional context and culture restrict and allows freedom of approach used	Structural factors influence educators' ability to implement	Educators' mention: Size of classes/institution (<i>e.g.</i> , smaller institution allows for more flexibility).	"Quest University is a small institution meaning instructor autonomy and low administrative overhead for implementing changes"
	Colleague and institutional expectations and support influence educators'	Educators' mention: Social pressure from colleagues' (restricts freedom). Freedom depends on the colleagues they work with. Educators need to consider how large changes to approaches used	"There is also social pressure to conform to the type of teaching done by my colleagues (even those it's not necessarily informed by best practices) so

	ability to implement	affect other courses and colleagues' (restricts freedom). Educators have no expectations from administration (allows freedom). Encouragement and support from administration to try new approaches (allows freedom).	that I get good teaching evaluations, and my students are primed to succeed in their courses." "Some approaches may not be approved by the administration, for different reasons."
	Policy imposed by the institution influences freedom to implement	Educators' mention: Policy restrictions from administration. Certain policies allow for more freedom.	"Our course management policy allows for freedom in course development with only slight restrictions on assessments at the end of term and the requirement that full online delivery can only be run with approval of the Department Council and Senate."
Department and subject area context restrict and allows freedom of approach used	Departmental expectations lower flexibility	Educators' mention: Collaborative decisions by department lower flexibility. Mandated assessments limit their flexibility. Approaches need approval by department or administration.	"A lot of Academic freedom to teach as long as course objectives are met but as a dept we work together to choose material and lab activities." "I can have a different teaching approach but must assess the same outcomes as equivalent units."
	Subject area influences flexibility	Educators' mention: Type and level of course have different flexibility of approaches used.	"It depends a bit on whether first year, second year or third year, how many students and which colleagues I am working with."
Educator role restricts and allows freedom of approach used	Educator position impacts level of flexibility for an approach used Single instructor of a course allows for more flexibility	Educators' mention: An educators' position allows them to have flexibility. Co-teaching courses restrict flexibility. Being a single instructor for a course allows more flexibility.	"The courses I currently teach are co-taught by other instructors and we must all teach in fairly similar ways as we must use the same supporting material (e.g., books) AND the same exams."

8.1.4.4 Educators' Knowledge

Educators' responses of the aspects of STICE they want to learn about were consistent with educators perceived level of knowledge of STICE. Over half of the participants indicated they had little to no knowledge of STICE (Figure S2). While fifteen participants (27%) indicated they had no knowledge as they had never heard of STICE before, the remaining participants self-reported some level of knowledge and described ways in which they had gained this knowledge. Identifying ways educators gain their knowledge on STICE can be useful for understanding where emphasis needs to be placed on communicating STICE, to reach all groups of chemistry educators.

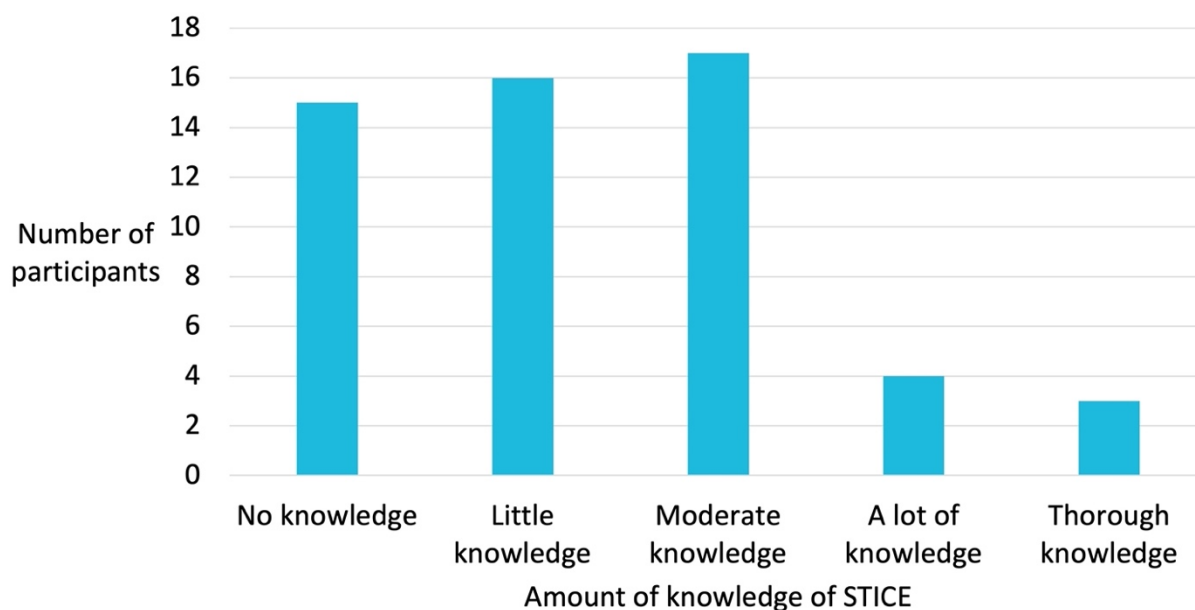


Figure S2. Educator's perceived level of knowledge on STICE (N = 55).

The number of ways chemistry educators gain knowledge on STICE was shown to increase across the knowledge groups. Educators who self-reported to have little knowledge (29%) on STICE typically gained their knowledge in one of four ways: conference presentations, websites (e.g., American Chemical Society), educational sessions on STICE, and discussions with colleagues (Figure S3). Educators with moderate knowledge (30%) on STICE typically gained their knowledge through one or two aspects and these aspects included the same ways

as the previous knowledge group with the addition of: publications on STICE, social media, direct participation with STICE projects, and familiarity of ST from different disciplines. Lastly, educators with a lot or thorough knowledge (12.5%) also reported they had gained knowledge in the same ways as the other two knowledge groups with the addition of: conducting STICE research, being a member of the IUPAC STICE project, and through teaching experiences. However, unlike the other two knowledge groups who reported one or two ways in which they gained STICE knowledge, this higher knowledge group had reported an average of three ways. These participants in the “a lot/thorough” knowledge group generally engaged in ways that involve communicating STICE to other groups of people. Educators did not report to gain STICE knowledge through textbooks or accreditation standards, which are other common means for knowledge construction.

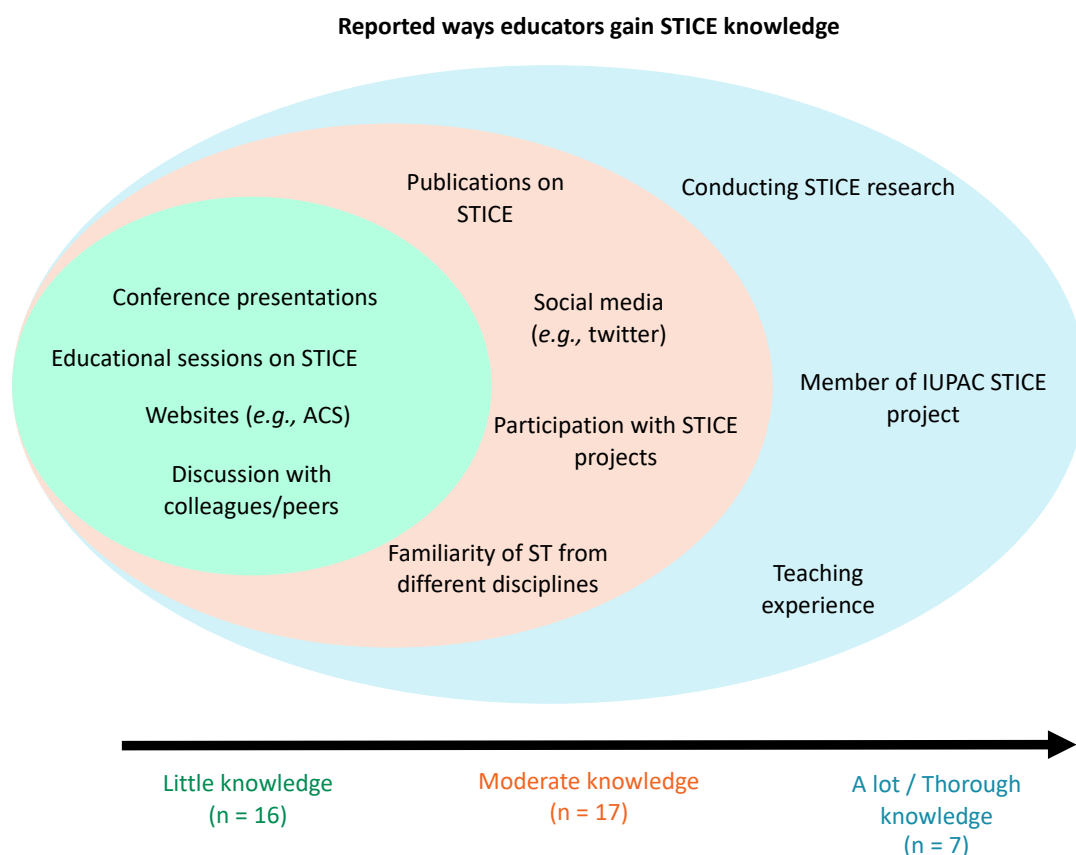


Figure S24. Reported ways chemistry educators gain knowledge on STICE.

Overall, educators reported gaining STICE knowledge through one of the two communication channels: 26 via mass media (*e.g.*, conferences, publications, chemistry organizations) and 14 via interpersonal (*e.g.*, educational classes, social media, discussion with colleagues/peers, familiarity from different context, participation with projects, conducting research, and teaching experience) communication. Only three educators reported gaining knowledge on STICE through an educational class on STICE. That low number suggests that there may not be many support mechanisms available for chemistry educators to learn about STICE and how to implement STICE into their chemistry courses or educators are not interested in attending workshops.

Educators' responses of the aspects of STICE they want to learn about was consistent with educators perceived level of knowledge of STICE (Figure S2). To understand what is required to educate educators on STICE, we specially asked participants to identify aspects of STICE they would like to know more about and what resources and tools they would need to implement STICE (Figure S4). Aside from educators primarily wanting ways to **effectively implement and integrate STICE into a course**, and **specific examples and applications of STICE being implemented and assessed by educators**, educators want to learn other aspects of STICE. Specifically, educators also wanted to know **how to engage in the essential characteristics and skills** of STICE, including: how to highlight emergent behaviours, how behaviours change over time, examining the relationship between parts of a system and how those interconnections lead to cyclic system behaviors, and how to limit the boundaries of a system being taught. Other areas that surfaced during analysis included educators wanting to **know the previous successes and failures** of ST as well as **evidence-based research and resources** (*e.g.*, long term impacts of ST on affective learning objective, how ST improves student outcomes, research proving ST is an effective approach, and a summary of theoretical frameworks on which ST is based). Communication networks (*e.g.*, other instructors to talk to and learn from their experiences), and general resources (*e.g.*, time, money, students, and freedom from administration) were two other resources participants indicated they would like to have but were reported less frequently. These findings can guide chemistry educator training

and workshops considering that there is a demand to create efficient, low-cost, hands-on workshops on STICE as most participants (69%) indicated they are interested and would attend workshops for various reasons (Table S6). Additionally, the results provide insight on the specific aspects of STICE and creation of STICE resources needed to educate educators on STICE so that they may be more willing to enact a STICE approach.

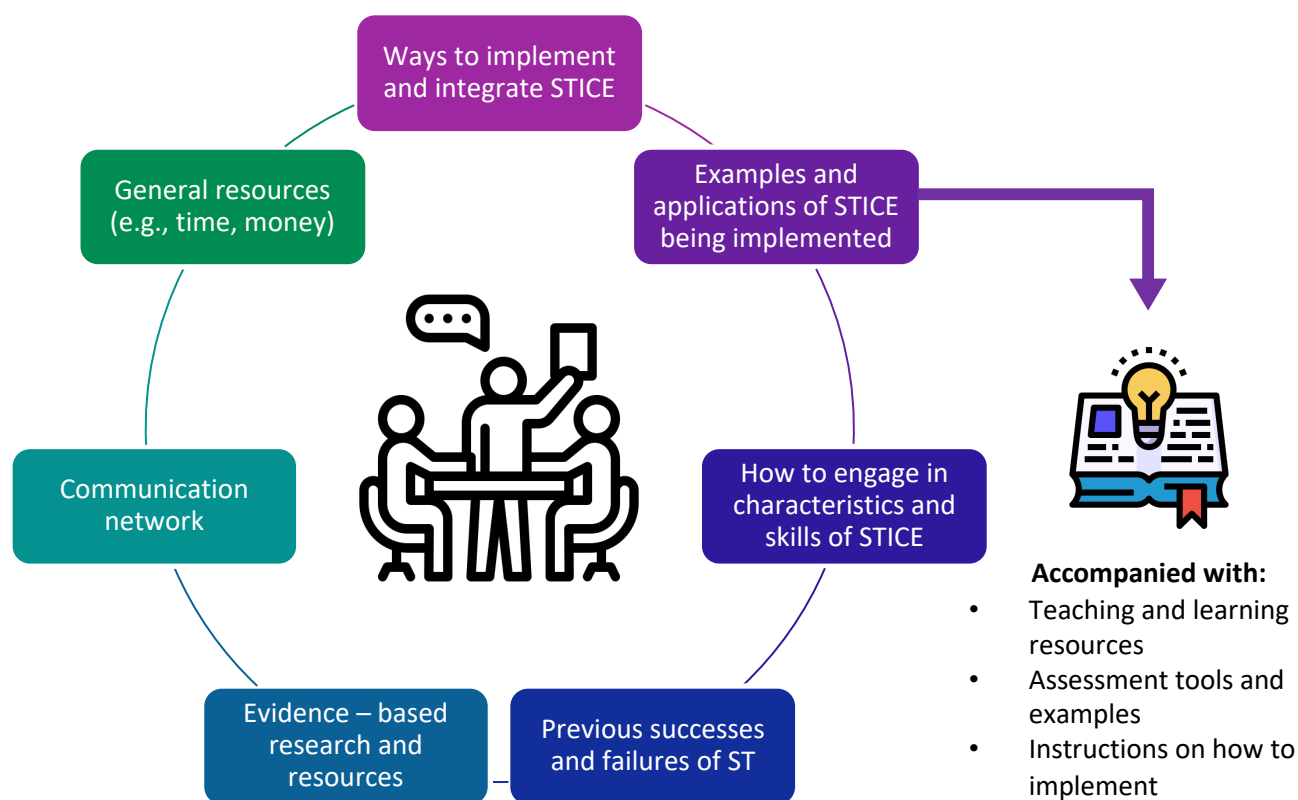


Figure S25. Reported resources that educators would like to have to implement STICE.

Here, we identified that efforts of change need to be placed on educators' thinking of the educator change model. Chemistry educators at the center of embracing new instructional approaches need to be supported as they transition to new, unfamiliar approaches like ST.¹⁵ Putting focus on the supports needed to educate chemistry educators on STICE will help eliminate the knowledge barrier for implementing STICE.

Table S4. Code book for educators' responses to their willingness to attend STICE workshops.

Themes	Categories	Description	Representative quotes
Educator's knowledge on STICE influences their willingness to attend STICE workshops	Would attend workshops to learn more about STICE and how to implement effectively	Educators' mention: They would attend STICE workshops to learn more about ST and how it is implemented into courses. They would probably not attend the workshops as they prefer to read about STICE.	"Yes - to learn more about it and how it is implemented."
	Would rather read more to determine if willing to explore		"Probably not. I would, however, read more about ST to determine if it is something I would be willing to explore further."
Educator's affect influences their willingness to attend STICE workshops	Educators are interested in new learning approaches	Mentioned they would attend STICE workshops because they are interested in learning new approaches.	"Yes - I am always interested in ways to improve my ability to teach, and I think in many ways it is our responsibility as educators to continue to learn ways to improve and ensure students get the most out of their courses"
Educator's beliefs influence their willingness to attend STICE workshops	Believes workshops on STICE will help improve their teaching	Educators' mention they would attend workshops because: They help improve their teaching. ST would help students foster understanding and problem-solving skills. Could provide structure across curriculum. ST is the latest technology and future of chemistry education.	"Yes - my teaching always improves as a function of attending workshops."
	Believes STICE will benefit students and is beneficially for the future of chemistry		"Yes. I think it can help provide structure across the curriculum."
Contextual factors influence educators' willingness to attend STICE workshops	Concerned with time restriction, format of workshop, and cost	Educators' mention attending STICE workshops depends on: Time permitting. Format and length of workshops. Cost of workshop.	"Depends in the format and length. It's interesting, but low on my priorities." "If they were truly hands-on workshops, yes. I don't have time to sit through any lectures."

8.1.5 Supplementary Theme 2: Educators report to have experience with STICE without knowing or specifically calling it ST

Chemistry educators' self-reported level of knowledge on STICE was shown to be consistent with their definitions on STICE. Due to participants' low level of knowledge, it was not surprising that eighteen of these participants only indicated one characteristic of ST in their definition (Figure S5). Additionally, twelve participants related ST to a different teaching or learning approach and seven participants simply indicated ST is a learning and/or teaching tool; 47% of which did not include any characteristic of ST in their definition.

Participants who incorporated more than one characteristic in their definition, primarily included: holistic approach, interconnections, applying chemistry to other contexts, and looking at variables that cause behaviours and outcomes (Figure S5). Five participants provided definitions that incorporated four or more characteristics of STICE; 60% included additional characteristics such as looking at behaviours that change overtime, identifying emergent effects of systems, and defining and working with boundaries of a system.

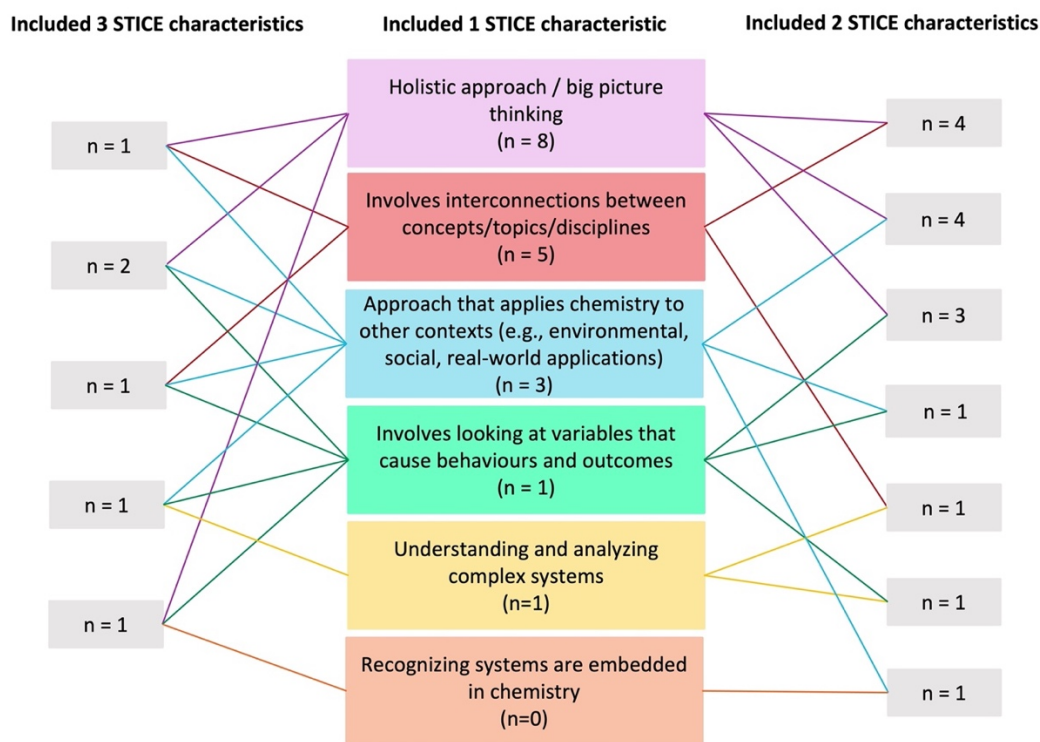


Figure S5. Combinations of STICE characteristics represented in chemistry educators' definitions of STICE.

8.1.6 Supplementary Theme 3: Some chemistry educators implement limited aspects of STICE when teaching chemistry in context

More than half (66%) of the participants from this study reported they have implemented ST or some aspects of ST into the courses they taught (Figure 5). Educators who have implemented STICE, primarily implemented two characteristics of STICE in the course(s) they teach: identifying how knowledge of chemistry connects to social, technological, economic, and environmental systems at work in our world and recognizing a system as a whole, not just a collection of parts (Figure S6). This finding aligns with characteristics identified in educators' definitions.

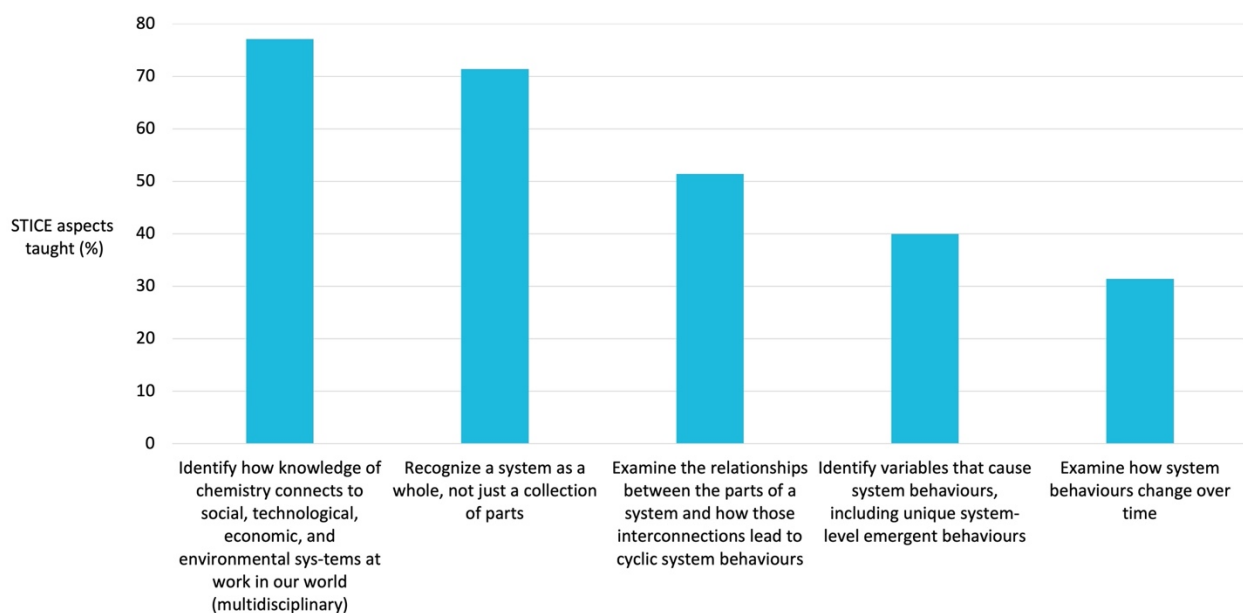


Figure S6. Aspects of a STICE approach that educators with experience implement to their courses.

STICE characteristics that involve aspects of systems behaviours (*e.g.*, identifying variables that cause system behaviours and examine how system behaviours change over time) were implemented less in the course(s) educators teach. This observation may be associated with educators' knowledge of STICE as sixteen participants had included some aspects of systems behaviours as part of their definition. Therefore, if more effort were targeted at educating educators on characteristics of ST that involve system behaviours, educators may be more equip and knowledgeable to implement these aspects into their course(s).

8.1.7 Supplementary Theme 4: Rating of barriers can guide priorities for educator and educational barriers

8.1.7.1 Student barriers of STICE

There was a range of perspectives for each individual barrier (Figure S7), as participants generally considered the following potential student barriers for STICE to have a slight to moderate extent (Table S7). Lack of experience using high level thinking skills needed for ST was perceived to have the largest extent of student barrier compared to the mean values of the other barriers listed. This finding suggests that high level thinking skills may not be practiced in chemistry courses; therefore, there is a larger learning gap required for students to engage in ST. Additionally, the learning gap required for students to engage in ST may be related to our previous finding that educators believe ST needs to be implemented at a specific level (generally higher-level courses) due to skill and knowledge levels of students.

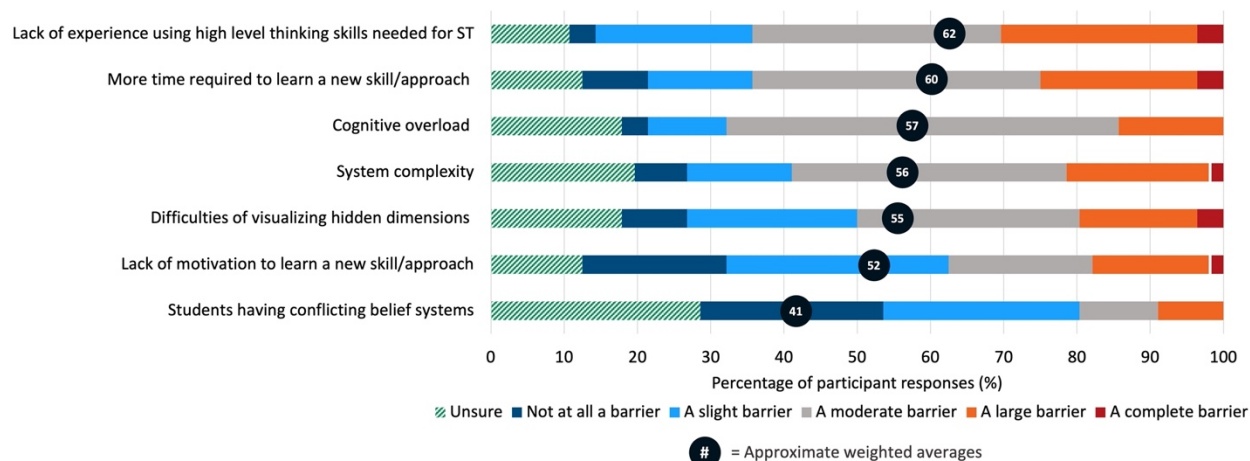


Figure S7. The extent of student barriers for STICE self-reported by chemistry educators. Circled values represent weighted averages of the extent of each barrier; these are approximations as the data is categorical.

Conflicting belief systems was shown to be the student barrier that participants were most unsure about. This suggests that these participants may not understand what conflicting belief systems means in the context of implementing STICE and aligns with the reported low ST knowledge of participants. However, out of all the student barriers, conflicting belief systems is observed to have the lowest extent of barrier for students engaging in STICE.

Table S7. Mean and standard deviation for perceived student barriers for STICE. Unsure responses have been removed for better understanding of categorical data.

Student Barriers	Mean	Std. Deviation	N
<i>Lack of experience using high level thinking skills needed for ST</i>	3.06	0.935	50
<i>More time required to learn a new skill/approach</i>	2.96	0.999	49
<i>Cognitive overload</i>	2.96	0.698	46
<i>Systems complexity</i>	2.93	0.939	45
<i>Difficulties of visualizing hidden dimensions</i>	2.78	1.031	46
<i>Lack of motivation to learn a new skill/approach</i>	2.43	1.099	49
<i>Students having conflicting belief systems</i>	2.05	1.011	40

8.1.7.2 Educator/Educational barriers of STICE

Table S8. Mean and standard deviation for perceived educator and educational barriers for STICE. Unsure responses have been removed for better understanding of categorical data.

Educator and Educational Barriers	Mean	Std. Deviation	N
<i>Educators' expertise on ST</i>	3.16	1.149	50
<i>Limited time to teach ST skills to students</i>	3.10	0.944	51
<i>Limited time to learn how to facilitate ST approaches</i>	3.08	0.997	51
<i>Limited teaching resources presently</i>	3.08	1.146	51
<i>Limited assessment tools</i>	2.96	1.113	51
<i>Limited research-based evidence of success of STICE</i>	2.57	1.109	46
<i>Limited flexibility within the curriculum</i>	2.53	1.280	53
<i>Educators' comfort level for adding ST to a course</i>	2.41	1.039	49
<i>Teaching ST takes away from depth in chemistry</i>	2.16	0.974	43
<i>Limited flexibility for implementing a new teaching approach</i>	1.78	0.985	49
<i>Educators' expertise in chemistry</i>	1.44	0.848	48

8.1.7.3 Kruskal Wallis tests of the three experience groups on the average extent of barrier

To further investigate the extent of each barrier, Kruskal Wallis tests were conducted to evaluate differences among the three experience groups on the average extent of barrier. The results of

the analysis indicate there was a significant difference in the medians for two student barriers:

system complexity ($H(2) = 8.199$, $p = 0.017$, $\eta_H^2 = 0.1476$, large effect size) and more time to learn

a new skill/approach ($H(2) = 6.934$, $p = 0.031$, $\eta_H^2 = 0.1073$, medium to large effect size) and two

educator barriers: *limited time to teach ST skills to students* ($H(2) = 7.504$, $p = 0.023$, $\eta_H^2 = 0.1147$,

medium to large effect size) and *educators' comfort level for implementing ST* ($H(2) = 6.511$, $p =$

0.039 , $\eta_H^2 = 0.0981$, medium to large effect size) (Figure S8 and Figure S9).

The effect size for each Kruskal Wallis test was computed using eta squared (η_H^2) (Table S9).^{16,17} Effect sizes of η_H^2 are based on Cohen (1988) benchmarks to define small

($\eta^2=0.01$), medium ($\eta^2=0.06$), and large ($\eta^2=0.14$) effects.¹⁸

Table S9. Kruskal Wallis test statistics and effect sizes for the four student, educator, and educational barriers based on educators' experience.

	Test statistic (H)	Asymptotic Sig.	eta squared (η_H^2)	Effect size**
Systems complexity	8.199	0.017*	0.1476	Large
More time required to learn new skill/approach	6.934	0.031*	0.1073	Medium – Large
Limited time to teach as an educator	7.504	0.023*	0.1147	Medium – Large
Educators' comfort level	6.511	0.039*	0.0981	Medium – Large

*Significant at the 0.05 level

**Effect size of η^2 based on Cohen (1988): small = 0.01; medium = 0.06; large = 0.14

A post-hoc analysis was conducted to evaluate pairwise comparison among the three experience groups by controlling for Type I error across tests using Bonferroni correction (Table S10 and S11). This test showed that for *system complexity* as a barrier, there was a significant difference of the extent of barrier between participants who have implemented ST and participants who have not implemented ST as well as between participants who have

implemented some ST principles and participants who have not implemented ST. Additionally, for the student barrier, *more time to learn a new skill/approach*, there was a significant difference of the extent of barrier between participants who have implemented ST and participants who have not implemented ST.

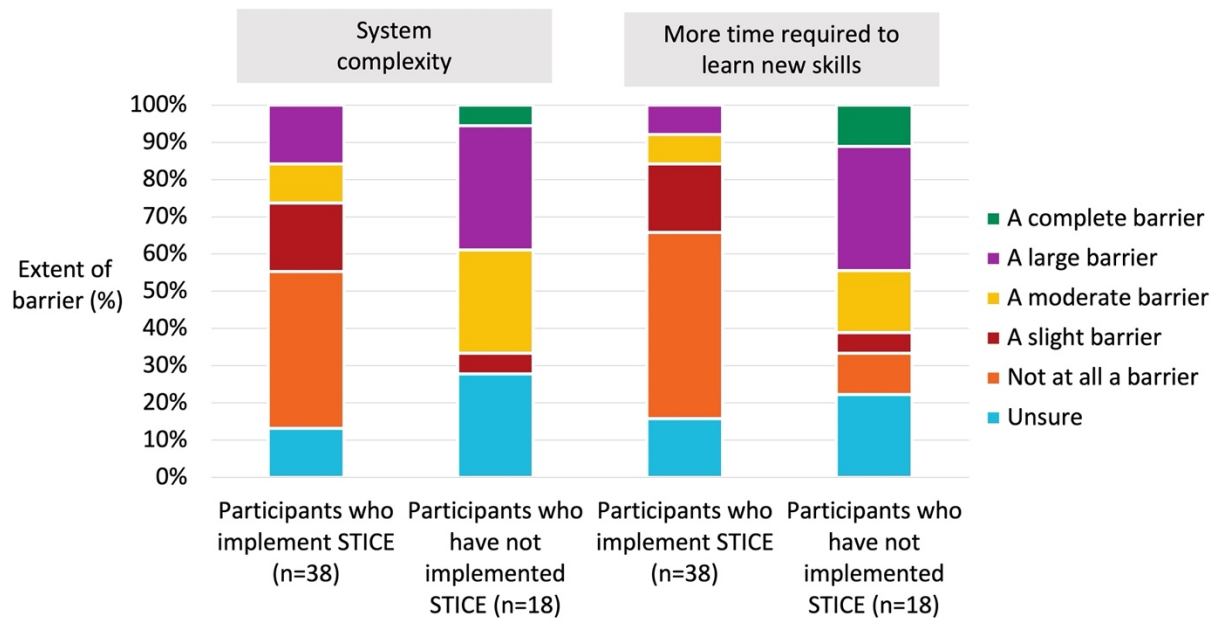


Figure S8. The extent of student barriers based on educators' experience with STICE: (left) system complexity, (right) more time required to learn new skill.

Table S10. Pairwise comparisons of experience groups for student barriers of STICE.

Experience Groups	System complexity			More time required to learn new skill		
	Test statistic	Asymptotic Sig.	Adjusted Sig. ^a	Test statistic	Asymptotic Sig.	Adjusted Sig. ^a
(1)-(2)	14.545	0.017	0.050	15.696	0.009	0.026
(1)-(3)	10.423	0.013	0.038	6.368	0.151	0.454
(2)-(3)	4.122	0.460	1.000	9.329	0.086	0.257

(1) = I have not implemented STICE

(2) = I have implemented STICE

(3) = I have implemented some aspects of STICE

Significance values adjusted by the Bonferroni correction for multiple tests

The significance level is 0.050

Additionally, for extent of the educator barrier, *limited time to teach ST skills to students*, had a significant difference between some of the experience groups. Specifically, differences were shown between (1) participants who have implemented ST and participants who have not

implemented ST and between (2) participants how have implemented some ST principles and participants who have not implemented ST. Likewise, *educators' comfort level* for implementing ST showed a significant difference in the extent between participants who have implemented ST and participants who have not implemented ST.

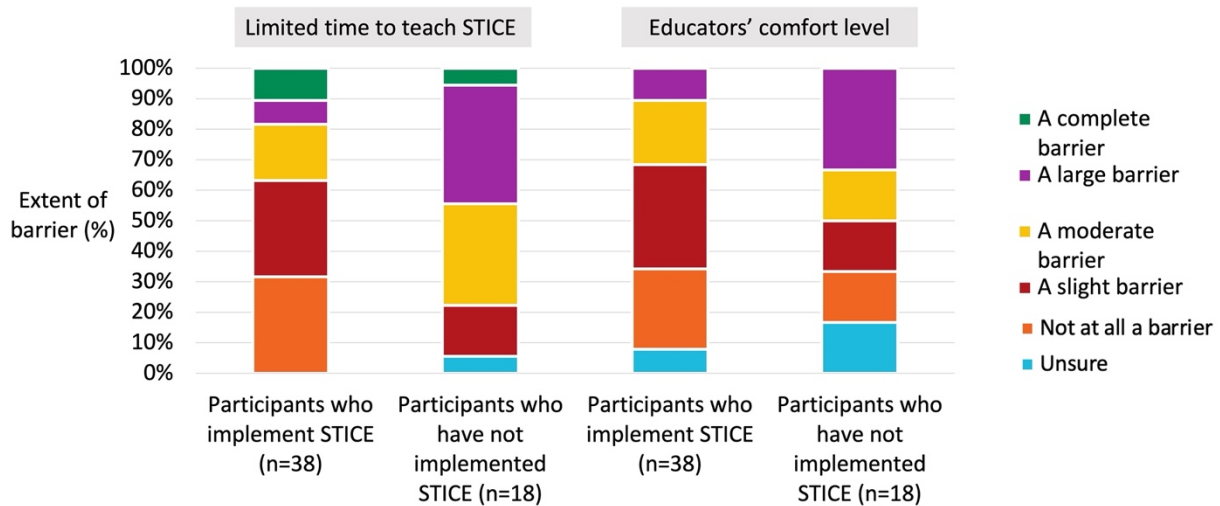


Figure S9. The extent of educator and educational barriers based on educators' experience with STICE: (left) limited time to teach STICE, (right) educators' comfort level with STICE.

Table S11. Pairwise comparisons of experience groups for educator barriers of STICE

Experience Groups	Limited time to teach			Educators' comfort level		
	Test statistic	Asymptotic Sig.	Adjusted Sig. ^a	Test statistic	Asymptotic Sig.	Adjusted Sig. ^a
(1)-(2)	16.681	0.008	0.025	15.338	0.011	0.033
(1)-(3)	1.953	0.654	1.000	4.515	0.312	0.936
(2)-(3)	14.728	0.014	0.041	10.822	0.052	0.156

(1) = I have not implemented STICE

(2) = I have implemented STICE

(3) = I have implemented some aspects of STICE

^aSignificance values adjusted by the Bonferroni correction for multiple tests

The significance level is 0.050

Some of these barriers may initially be perceived to have a greater extent but when implementing the approach, educators may notice they are no longer a barrier. This is shown through a participant who has experience with STICE, as they state:

I've already done it, so none of these are a barrier (any longer). We use ST as a design principle rather than learning objective, so we're not devoting time to teaching the skill of ST. We spent a lot of time to develop learning resources and assessments, and how to adapt our curriculum to allow for ST approaches, so those were barriers at first. We're still figuring out how best to implement ST approaches efficiently and practically, are doing the research now. The flexibility / comfort level concerns were never an issue.

8.1.8 Limitations

There are several limitations on what we may conclude or imply given the study design and analysis procedures. First, there is a potential for social desirability bias within these results as some of the data is positively skewed.¹⁹ Therefore, future studies would need to be conducted to minimize bias by revising questions in the questionnaire and allow more opportunities for participants to express negative perspectives.

While this study addressed general factors as outlined in the theoretical framework, future studies should investigate specific contextual factors (e.g., the level of student preparation, classroom environment, departmental expectations) to better understand how STICE can be integrated in institutions and within curricula. Additionally, we only were able to capture educators reported experiences of how they implement STICE. We were unable to identify if participants incorporate each aspect of STICE into their teaching. To identify how they actually teach STICE in their courses, recordings of their teaching or classroom observations would need to be conducted along with follow up interviews.

Lastly, due to the limited number of participants as secondary school educators in our study, we were unable to investigate the difference between secondary and post-secondary educators' perspectives about the barriers to implement STICE.

8.1.9 STICE educator Perspectives Questionnaire

Part 1 of Educator Questionnaire: Knowledge, Flexibility, Willingness, and Barriers

1. How much flexibility do you have with implementing new teaching approaches of any kind?

None (I am told which approach to use)	Little	Moderate	A lot	Complete (I can use any approach I want)
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Please explain your response above.

2. How much do you know about systems thinking in chemistry education (STICE)?

No knowledge	Little knowledge	Moderate knowledge	A lot of knowledge	Thorough knowledge
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If you have any knowledge of STICE, through what ways have you gained this knowledge?

3. How do you define systems thinking in chemistry education (STICE)? Please feel free to guess if you are not sure.

4. If provided with teaching resources on how to implement STICE, how likely would you integrate a ST approach into your course(s)?

Not at all likely	Not very likely	Somewhat likely	Very likely	Certain
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Please explain your response above.

5. What student barriers exist for implementing systems thinking (ST) into your course?

Unsure	Not at all a barrier	A slight barrier	A moderate barrier	A large barrier	A complete barrier
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List any other potential student barriers.

6. What educator/educational barriers exist for implementing systems thinking into your course?

Unsure	Not at all a barrier	A slight barrier	A moderate barrier	A large barrier	A complete barrier
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List any other potential educator/educational barriers.

Part 2 of Educator Questionnaire: Educators' experience with STICE

From current literature, systems thinking in chemistry education has been defined as:

An approach for examining and addressing complex behaviours and phenomena from a more holistic perspective.

A chemistry learner/professional who engages in a systems thinking approach should:

- (1) Recognize a system as a whole, not just a collection of parts.
- (2) Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviours.
- (3) Identify variables that cause system behaviours, including unique system-level emergent behaviours.
- (4) Examine how system behaviours change over time.
- (5) Identify how knowledge of chemistry connects to social, technological, economic, and environmental systems at work in our world (multidisciplinary)

Note: Please do NOT change your definition from part 1 of the educator survey

Orgill, M.; York, S.; & MacKellar, J. J. Chem. Educ. 2019, 96 (12), 2720-2729.

Mahaffy, P. G.; Matlin, S. A.; Whalen, J. M.; Holme, T. A. J. Chem. Educ. 2019, 96 (12), 2730-2741.

York, S.; Orgill, M. J. Chem. Educ. 2020, 97 (8), 2114-2129.

Based on the definition of systems thinking above, please choose the category that best represents your experience with systems thinking in chemistry education (STICE)

- Group 1: I have not implemented systems thinking in the course(s) I teach
- Group 2: I have implemented systems thinking into the course(s) I teach
- Group 3: I have implemented systems thinking principles into the course(s) I teach (some aspects of systems thinking)

Questions for part 2 of questionnaire	Group 1	Group 2	Group 3
1. Could you see yourself implementing ST in your course(s)? (All, some, or no courses) Please explain.	X		
2. If you plan on implementing ST, how would you implement ST into your course(s)?	X		
3. What aspects of systems thinking in chemistry education would you like to know more about?	X	X	X
4. What resources or tools would you like or need to have in order to be able to introduce and/or assess systems thinking in chemistry education into your course(s)?	X	X	X
5. Would you attend ST workshops on how to implement ST as an educator? Why or why not?	X	X	X
6. Please describe how you have taught or are teaching chemistry with a ST approach (even if called something different)?		X	X
7. Approximately when did you start implementing systems thinking in chemistry education? (Please indicate the course if applicable)		X	
8. In what ways is systems thinking being assessed (formative and/or summative) in that/those course(s)?		X	X
9. What methods do you use to overcome some of the barriers you've encountered with systems thinking?		X	
10. Do you create your own systems thinking resources or use existing ones? Please explain.		X	
11. Do you think it is important for educators to implement a ST approach to their courses? Why or why not?		X	X
12. Which aspects of a systems thinking in chemistry education approach do you teach to your students? Check all that apply.		X	X
• Recognize a system as a whole, not just a collection of parts.			

- Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviours.
- Identify variables that cause system behaviours, including unique system-level emergent behaviours.
- Examine how system behaviours change over time.
- Identify how knowledge of chemistry connects to social, technological, economic, and environmental systems at work in our world (multidisciplinary)

Part 3 of Educator Questionnaire: Demographic questions

1. At what institution and in what country do you teach?
2. What is your role?
 - **Assistant professor; Associate professor; Full professor; Lecturer or Instructor; Professor Emeritus; Senior lecturer or instructor; Teacher (grades 9-12)**
3. Approximately how many years have you been teaching? (not including teaching assistantships)
 - **1 to > 30**
4. What courses do you teach? (Please include course code and level)
5. What is your gender? (Note: the "other" category in this question is interpreted as the above options not applying to you, and you prefer to identify as _____)
 - **Woman; Man; Transgender; Non-binary; Prefer not to answer**
6. A) Do you identify as Indigenous, that is, First Nation (North American Indian), Métis or Inuk (Inuit)? (question taken from NSERC Self-identification Questionnaire)
 - **Yes; No; Prefer not to answer**

B) If answered "Yes", select the group(s) that you identify with. (question taken from NSERC Self-identification Questionnaire)

 - **First Nation; Inuit; Métis; Prefer not to answer**
7. Select the population group(s) you identify with. Note: if you answered "Yes" to question 6a (i.e., indicating you are an Indigenous person), select "Population group not listed above" for this question. You can also select from the list any other population group that applies to you. (question taken from NSERC Self-identification Questionnaire)
 - **Arab; Black; Chinese; Filipino; Japanese; Korean; Latin American; South Asian (e.g., East Indian, Pakistani, Sri Lankan, etc.); Southeast Asian (including Vietnamese, Cambodian, Laotian, Thai, etc.); West Asian (e.g. Iranian, Afghan, etc.); White; Prefer not to answer; Population group not listed above. I identify as _____ (indicate in other option to specify)**
8. Is there anything else you would like to add?

8.1.10 References

- (1) Gess-Newsome, J.; Southerland, S. A.; Johnston, A.; Woodbury, S. Educational Reform, Personal Practical Theories, and Dissatisfaction: The Anatomy of Change in College

- Science Teaching. *Am. Educ. Res. J.* **2003**, 40 (3), 731–767.
<https://doi.org/10.3102/00028312040003731>.
- (2) Clarke, D.; Hollingsworth, H. Elaborating a Model of Teacher Professional Growth. *Teaching and Teacher Education*, 18(8), 947–967. *Teach. Teach. Educ.* **2002**, 18, 947–967. [https://doi.org/10.1016/S0742-051X\(02\)00053-7](https://doi.org/10.1016/S0742-051X(02)00053-7).
 - (3) Woodbury, S.; Gess-Newsome, J. Overcoming the Paradox of Change without Difference: A Model of Change in the Arena of Fundamental School Reform. *Educ. Policy* **2002**, 16 (5), 763–782. <https://doi.org/10.1177/089590402237312>.
 - (4) Chyung, S. Y. Y.; Roberts, K.; Swanson, I.; Hankinson, A. Evidence-Based Survey Design: The Use of a Midpoint on the Likert Scale. *Perform. Improv.* **2017**, 56 (10), 15–23. <https://doi.org/10.1002/pfi.21727>.
 - (5) Lincoln, Y. S.; Guba, E. G.; Pilotta, J. J. *Naturalistic Inquiry*; Newbury Park, CA: Sage., 1985.
 - (6) Creswell, J.W., & Miller, D. L. Determining Validity in Qualitative Inquiry. *Theory Pract.* **2000**, 39 (3), 124–130. <https://doi.org/10.1207/s15430421tip3903>.
 - (7) Reeves, T. D.; Marbach-Ad, G. Contemporary Test Validity in Theory and Practice: A Primer for Discipline-Based Education Researchers. *CBE Life Sci. Educ.* **2016**, 15 (1), 1–9. <https://doi.org/10.1187/cbe.15-08-0183>.
 - (8) Williams, M.; Moser, T. The Art of Coding and Thematic Exploration in Qualitative Research. *Int. Manag. Rev.* **2019**, 15, 45.
 - (9) Saldaña, J. *The Coding Manual for Qualitative Research*; 2009.
 - (10) Anney, V. N. Ensuring the Quality of the Findings of Qualitative Research: Looking at Trustworthiness Criteria. *Polit. Sci.* **2014**.
 - (11) 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.
 - (12) Boyatzis, R. E. *Transforming Qualitative Information: Thematic Analysis and Code Development*; Sage Publications, Inc: Thousand Oaks, CA, US, 1998.
 - (13) Field, A. *Discovering Statistics Using IBM SPSS Statistics*; Introducing statistical methods; SAGE Publications, 2013.
 - (14) Rogers, E. M. *Diffusion of Innovations*; Free Press: New York, 2003.
 - (15) Weaver, G. C.; Burgess, W. D.; Childress, A. L.; Slakey, L. *Transforming Institutions: Undergraduate STEM Education for the 21st Century*; 2015.
 - (16) Tomczak, M.; Tomczak, E. The Need to Report Effect Size Estimates Revisited. An Overview of Some Recommended Measures of Effect Size. **2014**, 21, 19–25.
 - (17) Cohen, B. H. *Explaining Psychological Statistics, 3rd Ed.*; John Wiley & Sons Inc: Hoboken, NJ, US, 2008.

- (18) Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed.; Lawrence Erlbaum Associates: New York, NY: Routledge Academic, 1988.
- (19) Larson, R. B. Controlling Social Desirability Bias. *Int. J. Mark. Res.* **2019**, *61* (5), 534–547. <https://doi.org/10.1177/1470785318805305>.

8.2 Appendix 2: Supporting Information for Chapter 3

Supporting Information: Identifying chemistry students' baseline systems thinking skills when constructing system maps for a topic on climate change

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8.2.1 S1. Methods

8.2.1.1 S1.1. Instrument and procedure for data collection

The pre-test for this study consisted of cognitive and affective instrument and a ST question. The cognitive and affective instruments used for this study were the Attitude towards the Subject of Chemical Inventory version 2 (ASCI. v2)¹ to assess attitudes towards chemistry and a Climate change awareness survey to assess student perceptions on climate change. These instruments were repeated to see how the learning experience influenced their affective domain and knowledge construction. Data from these instruments are being analyzed separately, with focus on affective domain effects of ST. The short response pre-test ST question was designed to assess participants' prior knowledge on ST.

The following information below describes additional details related to the three ST tasks.

For task 1, we used prompts on a google form to provide opportunities for students to demonstrate ST skills related to **system as a whole**, **interconnections**, and **boundaries**. The questions in the google form for task 1 asked participants to describe and explain how their system would change when removing a concept from their system. These questions were prompted to identify *if* and *how* students demonstrated skills related to the essential characteristic, **behaviors over time**.

To avoid the use of ST terminology, we asked participants to create a visual representation instead of calling it a system. Most systems produced by participants were in the form of a concept map.

For task 2, we asked participants to screen record to identify how they navigated through the simulation and identify concepts added to their systems.

Lastly, task 3 used recording devices integrated in Zoom to capture participants' experiences, and interactions with other participants in the study. We asked participants to identify similarities and differences between their systems to prompt participants to identify **emergent behaviors**.

8.2.1.2 S1.2. Context and Setting

While data was collected for both undergraduate and graduate students, we focused this study on the undergraduate student data, in order to have well-focused research questions and deeply share the rich findings. With separate research questions, we are currently analyzing the graduate student data.

Each iteration of the intervention allowed up to eight students to participate and was conducted via Zoom, a video conferencing software that allows one or more parties to meet virtually.

Seventeen students completed a demographic survey where nine declared they were in the first year in their undergraduate degree, seven declared second year, and one declared third year of their studies.

The most represented declared majors amongst recruited students include Biomedical Science, Biopharmaceutical Science, Health Science, and Biochemistry. Other majors included Chemistry, Human Kinetics, Biotechnology, and Biology.

8.2.1.3 S1.3. Theoretical Framework

Information Processing Theory. This theory guided our research by understanding how learners can use their prior knowledge in a particular learning environment (e.g., ST intervention) to determine what parts will be embedded in their systems and what parts are not

(e.g., components, relationships, organization, granularity, system behaviors). The first task required learners to use their prior knowledge to construct a system map. The second task allowed new information to be presented to the learner in a meaningful manner by linking new concepts to the learners' prior knowledge to potentially expand their system map. The third task altered the learning environment (i.e., collaborative setting) to allow learners to link new concepts in a different way.

Information processing begins when information (e.g., visual, auditory) enters through sensory registers.² Information that is perceived useful will enter working memory (WM), the rest will be discarded. WM is a temporary storage space that holds a limited amount of information for a few seconds to minutes. Information in WM can be retained through rehearsal and linked with already stored information in long-term memory (LTM). This information can be encoded (i.e., converting information into a form that is usable in the brain's storage system) into LTM, which can be influenced by, elaboration, organization, and link with existing knowledge structures.² Unlike WM, LTM is a memory storage that has the capacity to hold information for longer periods (e.g., days, months, and years). When learners transfer new information from WM to LTM, the learner must choose to integrate the new information by perceiving it as meaningful and linking it to their prior knowledge.⁴⁻⁶ Doing so, the learner is actively constructing their own knowledge.⁷⁻⁹ Therefore, to help learners connect new knowledge with existing knowledge and integrate the new knowledge in LTM is to present the information in a meaningful way and identify and engage with learners' prior knowledge.

Concept mapping. The two most investigated scoring methods for concept mapping are structural and relational. The structural method assigns weighted scores based on the concept map's hierarchical structure, concept-links, and cross-links.¹⁰ The hierarchical structure of a concept organizes concepts with the most general concepts (e.g., animals) at the top of the map and more specific concepts (e.g., dogs) and examples (e.g., cockapoo) arranged hierarchically below. Concept-links are the relationships between concepts in the map, accompanied by linking words or phrases. Cross-links are the long connections between concepts in different domains or paths of the concept map. Cross-links help us understand how different domains of

knowledge are related to one another. On the other hand, the relational method focuses more on the quality of the links in a concept map, without drawing importance on the structure of the map.¹⁰ Since we were only interested in investigating skills students could demonstrate, we did not use the relational scoring method as we were not interested in determining the correctness of links. Considering we conducted a qualitative study, we chose not to use weighted scores for scoring concept maps. Instead, we counted the number of occurrences of the aspects present in each concept map.

8.2.1.4 S1.4. Analytical Framework

Granularity. Granularity has been used in prior theoretical work related to chemistry students' reasoning¹¹⁻¹⁴ and has been identified as a key aspect of systems thinking.¹⁵⁻¹⁷ Researchers have identified that complex systems are characterized by distinct, interdependent levels of organization (granularity) and systems thinkers need to develop a sense of, and an ability to think between these levels in a system.^{15,18,19} Thinking between levels can be exemplified by looking at how a change in behavior of a concept at one level of organization (i.e., macroscopic) could lead to changes to a concept at a different level of organization (i.e., submicroscopic).¹⁵

Environmental and Sustainability triangular model. Researchers have indicated that systems thinkers need to understand how the system of focus may affect or be affected by other contextual factors and how the system may be a component of a larger system.¹⁵ Considering how human action and policies affect a system, engaging with these skills could prepare citizens to understand the ethical dimensions of human activity and how changes to ethical action can address complex global problems.^{15,18,20,21} This model is one way to look at the types of connections participants make in their system maps.

The model highlights crucial aspects of environmental and sustainability issues, which include the individual, nature, and societal contexts as well as their inter-woven relationships. We coded a connection as "Individual" when students related human beings (as individual and social being) being confronted with environmental issues. We coded a connection as "Nature" when students made connections related to nature (e.g., climate change). We coded a

connection as “Society” when students mentioned norms and values about the social, economic, political organizations, and their conceptions of justice and democracy. In addition to the individual contexts in the model, connections can also incorporate two contexts. The **nature and society** context includes participants’ conceptions about both societal effects on nature and nature’s effect on society. The **individual and society** context focuses on how individuals are influenced by societal norms and how the formation of societal norms is affected by people. The **individual and nature** context includes the participant’s conceptions of attitudes and behaviors that affect nature. The **society and chemistry** context includes participants’ conceptions of how social, economic, or political organizations or functions influence chemistry and/or how chemistry influences these organizations or functions. The **nature and chemistry** context includes participants’ conceptions of how climate change concepts and processes influence chemistry and/or how chemistry influences climate change. The **individual and chemistry** context includes participants’ conceptions of how human action influences chemistry and/or how chemistry influences humans.

This model has previously been used in environmental education research to investigate students’ solutions to the challenge of balancing economic development with climate change mitigation, focusing on societal responses to the climate change issue.²² Semi-structured pre- and post-interviews were conducted with 12 students to compare students’ decision making before and after being provided with different perspectives and information. In the interviews, the students were tasked with deciding whether a car factory should be set up near a village with a coal mine. The dilemma between developing the economy and mitigating climate change was indicated. In the pre-interviews, students decided to set up the car factory because they believed economic development and social welfare were most important. The analysis uncovered that students: (1) tended to argue that changing people’s old-fashioned notions is important (individual coded), (2) argued that damage to nature is a necessary step in sustaining economic growth and prosperity (nature coded), and (3) argued for economic development through the car factory. However, in the post-interviews, students decided not to set up the factory due to the challenges of setting up and running a business. The students

focused more on the societal aspect, discussing challenges of getting money, transporting, and selling cars, and proposing alternative business ideas to develop the economy. We used the model in a similar fashion by analyzing students' reasoning and the types of connections they made related to climate change. However, we did not provide a decision-making prompt in the ST intervention which led to a wide range of connections to these contexts. The relatively broad description for each code as defined in environmental education study allowed us to use this model in our study.

8.2.1.5 S1.5. Validity evidence

We addressed the validity of the findings using well-established methods such as, content validation, triangulation, disconfirming evidence, and peer debriefing.^{23,24} Content validity was performed before data collection to assess the quality of responses to questions and activities in the ST intervention. Here, two experts who research STICE engaged in the ST intervention and provided comments to improve the questions in the ST tasks. Additionally, a pilot of the ST invention was conducted with four chemistry graduate students and two undergraduate chemistry students as these students represented the appropriate group of participants for this study. All comments and feedback were acknowledged and changes to items were made accordingly.

Triangulation was another method used prior to data collection. This validity procedure involved us converging multiple and different sources of information to form themes in a study.²² We incorporated triangulation into the design of our study by using multiple and different methods to collect evidence on how students demonstrate ST skills (e.g., visualizations, google form, audio, and screen recordings). Validity evidence of the findings was established by relying on multiple forms of evidence instead of a single data point in the study.²³

In addition to collecting validity evidence during the design of our study, we also used methods throughout data analysis to maximize the trustworthiness of our findings. Disconfirming evidence is one method we used that involves searching through the data for evidence that disconfirms preliminary themes. Initially, we found preliminary themes about

what skills chemistry students could naturally demonstrate. However, when looking back at the data, we realized the data was not fully encapsulated in these themes. Therefore, we further investigated the skills to identify what aspects of the skills students did not demonstrate. Hence, our second research question was developed.

Peer-debriefing was used throughout the duration of the study. Regular sessions between the researchers and members of the Flynn Research Group allowed in-depth questions to be asked about the methods and interpretations and helped to address any assumptions and/or biases present in the analysis. This process maximized the credibility of the results.²⁴

Lastly, we provided the ST intervention and data analysis procedures clearly in the SI. This approach was similar to an audit trail requiring the lens of individuals external to the project to establish credibility.²³

8.2.1.6 S1.6. Assembly of data for system maps

To ensure we did not miss any information on how participants demonstrated ST skills, we assembled the responses from the Google form and transcribed audio scripts onto participants system maps to visualize all possible connections made by participants. All the concepts and connections present in participants system maps were transferred to Microsoft Excel for further analysis of ST skills. Figure S1 represents a participants system map at the end of the ST intervention before data assembly. Before adding additional data to the system maps, the first author made the visualization of concepts and connections amongst system maps consistent to prepare for data analysis. Consistency was achieved by (1) adding red arrows between two different concepts that were implicitly present and/or (2) breaking down sentences present in system maps to identify all concepts and connections involved. For example, Figure S1 shows an implicit connection between farmland and potential forest made by participant 12; therefore, a red arrow was added between these concepts to make the connection visible for data analysis. Additionally, the sticky note containing “crops for humans and animals” is example of a term that was broken down into three concepts associated with connecting arrows. Next, the participants system maps were expanded to include concepts and connections from google form responses (blue text and arrows) and verbal explanations of

system map from task 3 (purple text and arrows) (Figure S2). Figure S3 shows google form responses and transcribed audio recording data produced by participant 12. Bolded text in Figure S3 represents new concepts and connections that were added to the participants system map.

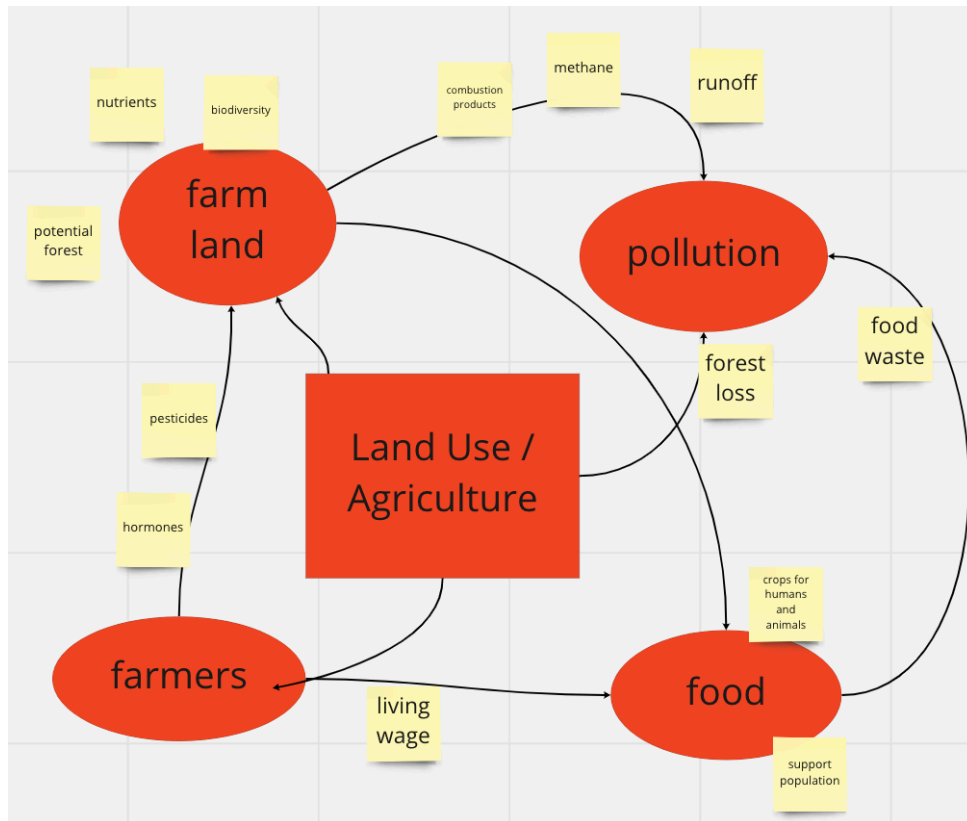


Figure S1. Original example of participants' (P12) system map from the ST intervention before assembly of data.

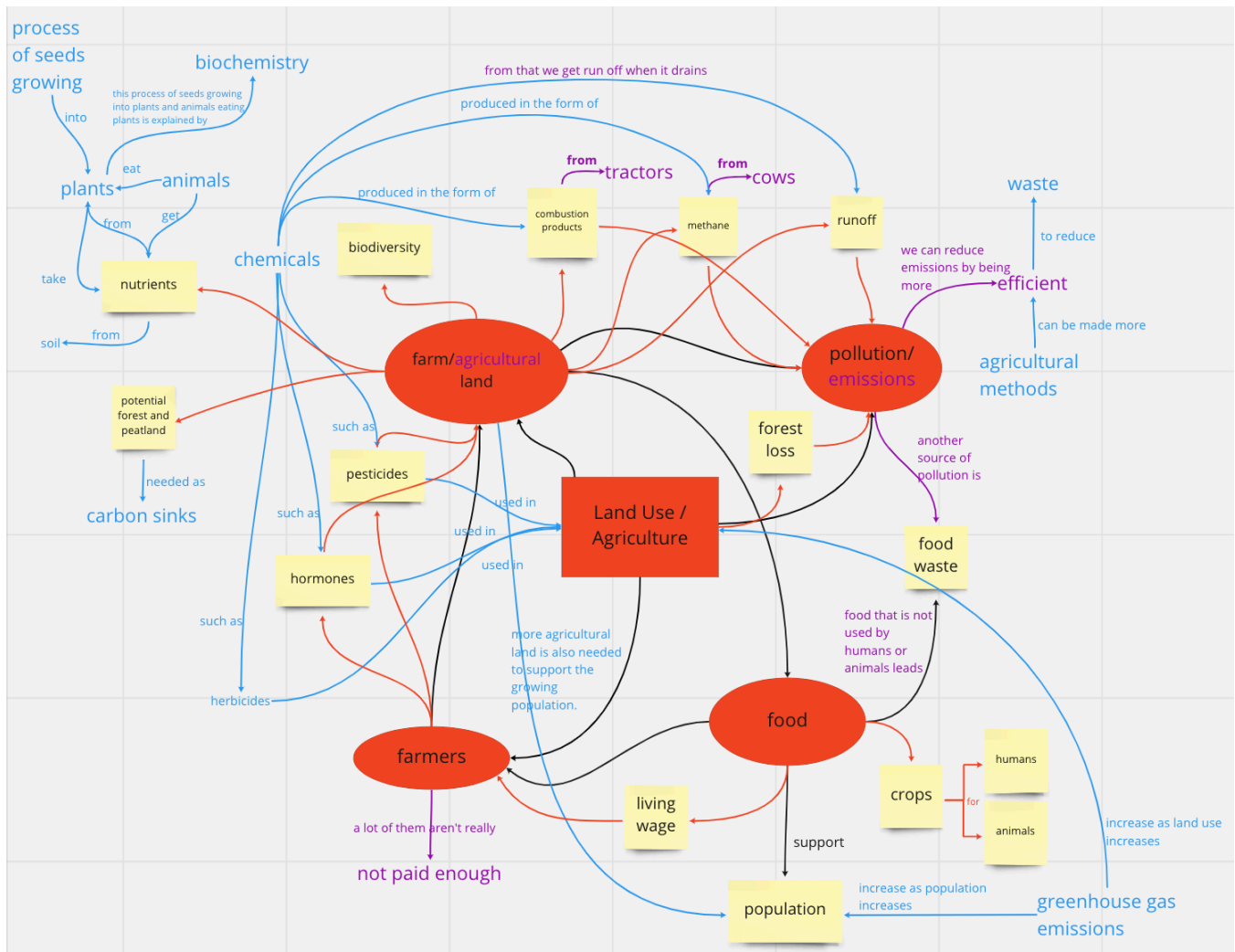


Figure S2. Participants' (P12) system map expanded based on assembly of data from google form responses and transcribed audio scripts. The blue, red, and purple text and arrows represent additional concepts, connections, and/or propositions from multiple sources of data. Blue represents data from google form responses. Purple represents data from verbal explanations of system maps. Red represents the researcher expanding participants' connections from their original system map.

response from task 1 - google form

Chemicals such as fertilizers, pesticides, herbicides, and hormones are used in agriculture. They are also produced in the form of methane, combustion products from machines, and runoff. **In addition, the process of seeds growing into plants and animals eating plants can be explained by biochemistry. Plants take nutrients from the soil and animals get their nutrients from plants.**

responses from task 2 - google form

Greenhouse gas emissions increase as population and land use increases. Forests and peatland are needed as carbon sinks. However, agricultural land is also needed to support the growing population. Agricultural methods can be made more efficient to reduce waste.

Transcribed audio script from task 3 - explanation of system map

But um, I guess for me, like I focus more on like, some connections, like some, some of our categories, I guess for mine, it can all be under this farmland area. But um, in terms of chemistry, I guess, going when we do farming, yeah, we use herbicides, pesticides, and hormones and animals. And then from that we get, run off when it drains and then obviously, methane from cows, and then also we have the combustion products from tractors and stuff like that. And then another source of pollution, or emissions is the food waste, because instead of being used by animals or humans, it's just put to waste and **then all those resources um were pretty much useless.** And yeah, **I guess like the big point that we got from the simulation,** you've talked about that, which is the balance between forest areas and land areas. I mean, I farmland. **And I guess another thing I had is like, more of a social aspect, which is for farmers, like a lot of them aren't really paid that much.** Some of them are almost like slaves. So and then also, **the fact that we have a growing population.** So I guess we can be more like, agriculture land should be increasing, **but I guess we can reduce emissions by being more efficient, while at the same time supporting the growing growing population.** I feel it's easy to like dismiss the reduction of the Amazon rainforest. But those people in Brazil kind of have to do it to actually live.

Figure S3. Participants' (P12) data from google form responses and transcribed audio recording.

8.2.1.7 S1.7. Development of systems thinking skills for analysis

The following ST skills are grouped by main characteristics and sorted based on being more analytical or more holistic in nature. The 15 STICE skills proposed by Orgill and York were compared to other ST skills found by other literature sources from several different disciplines. Critiques were made to these fifteen skills based on what was found in the

literature (Table S1). The STICE skills were revised, creating a total of twenty skills (Table S2). When figuring out how to assess these skills, we made the decision to remove nine of these twenty skills from the analysis based on various reasons as described in Table S3.

Table S1. Critiques made to STICE skills proposed by Orgill and York based on ST literature.

Original STICE skills proposed by Orgill and York		Our critique on the skill based on ST literature
Recognize a system as a whole, not just as a collection of parts	Examine a system as a unified whole (More holistic)	There are two components to this skill: - Able to see and think big picture ^{20,25-30} - Identify the purpose of the system ^{26,31,32}
	Examine the organization of components within the system	From literature search, organization was looked at in two dimensions - Identify and explain various levels of organization in a system ³¹⁻³⁹ (hierarchy/granularity – systems consist of partial systems categorized at diff levels of organization) - Thinking back and forth between different levels of organization in a system ^{34,39-42}
	Identify the individual components and processes within a system (More analytical)	No comments
Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviors	Identify the ways in which components of a system are connected (More analytical)	- This skill potentially lacks the key component of causality or effects of the connection - Could look at both the causal and correlational relationships among system components ⁴¹
	Examine positive and negative feedback loops within a system	- A dimension to this is just having feedback loops in system Ex: identify dynamic relationships within the system, including feedback loops ^{35,36,38,41,43,44}
	Identify and explain the causes of cyclic behaviors within a system (More holistic)	Possible to have cyclic relationships with ^{20,45} and without cause ^{28,42}

Identify variables that cause system behaviors, including unique system-level emergent behaviors	Identify the multiple variables that influence a given system level behavior; consider the potential effects of stochastic and “hidden” processes on the system-level behavior (More analytical)	Potentially break into two skills - Identify the multiple variables that influence a given system level behavior^{20,45} - consider the potential effects of stochastic and “hidden” processes on the system-level behavior^{26,42}
	Examine the relative, potentially nonlinear, effects that multiple identified variables have on a given system-level behavior	No comments
	Identify, examine, and explain (to the extent possible) emergent system-level behaviors (More holistic)	No comments
Examine how system behaviors change over time	Identify system-level behaviors that change over time (More analytical)	- Need to determine difference between system-level and non-system level behaviors - Terminology can be simplified to using “system” instead of “system-level behaviors”^{20,41,42,45,46}
	Describe how a given system-level behavior changes over time	
	Use system-level behavior-over-time trends under one set of conditions to make predictions about system-level behavior-over-time trends under another set of conditions (More holistic)	
Identify interactions between a system and its environment, including the human components of the environment	Identify and describe system boundaries (More analytical)	Another component to this skill is creating boundaries ^{41,45,46}

	Consider possible effects of a system's environment on the system's behaviors; consider how the system under study might be a component of and contribute to the behaviors of a larger system	Potentially break into two skills - Consider possible effects of a system's environment on the system's behaviors³⁵ - consider how the system under study might be a component of and contribute to the behaviors of a larger system^{45,47}
	Consider the role of human action on current and future system-level behavior (More holistic)	- May not need to be separated (human vs other) as part of boundaries - Skill may be more about making comparisons to other contexts/ describing a system from a different perspective^{25,26,28-30,36,38,42,48}

Table S2. Revisions made to STICE skills based on critiques.

Original STICE skills proposed by Orgill and York	Our modifications made to ST skills
Examine a system as a unified whole (More holistic)	Examine a system as a unified whole
	Identify the purpose of the system
Examine the organization of components within the system	Identify various levels of organization in a system
	Organize components and place them within a framework of relationships
	Think back and forth between different levels of organization in a system
Identify the individual components and processes within a system (More analytical)	No revisions made
Identify the ways in which components of a system are connected (More analytical)	No revisions made
Examine positive and negative feedback loops within a system	No revisions made
Identify and explain the causes of cyclic behaviors within a system (More holistic)	No revisions made
Identify the multiple variables that influence a given system level behavior; consider the	Identify the multiple variables that influence a given behavior on a system

potential effects of stochastic and “hidden” processes on the system-level behavior (More analytical)	Consider the potential effects of stochastic and “hidden” processes on the behavior of a system
Examine the relative, potentially nonlinear, effects that multiple identified variables have on a given system-level behavior	No revisions made
Identify, examine, and explain (to the extent possible) emergent system-level behaviors (More holistic)	No revisions made
Identify system-level behaviors that change over time (More analytical)	Identify behaviors that change over time
Describe how a given system-level behavior changes over time	Explain and predict how a system has changed and will change over time
Use system-level behavior-over-time trends under one set of conditions to make predictions about system-level behavior-over-time trends under another set of conditions (More holistic)	Use behavior-over-time trends under one set of conditions to make predictions about behavior-over-time trends under another set of conditions
Identify and describe system boundaries (More analytical)	Identify, describe, and create system boundaries
Consider possible effects of a system’s environment on the system’s behaviors; consider how the system under study might be a component of and contribute to the behaviors of a larger system	Consider possible effects of a system’s environment on the system’s behaviors
	Consider how the system under study might be a component of and contribute to the behaviors of a larger system
Consider the role of human action on current and future system-level behaviors (More holistic)	No revisions made

Table S3. ST skills not used in analysis of this study along with reasons for decision to exclude skill.

ST skills not used in analysis	Reasons why ST skill not used in analysis
Examine a system as a unified whole	We were not sure how to assess this skill.
Identify the purpose of the system	In this study we did not ask participants to define the purpose of their system map. Therefore, we cannot draw any conclusions on what we think the purpose of their system maps may be.

Examine positive and negative feedback loops within a system	This skill is embedded in the following skill, “identify the ways in which components of a system are connected”; therefore, we believed we did not need to assess individually.
Identify and explain the causes of cyclic behaviors within a system	We did not ask participants to identify or explain causes in their system maps
Consider the potential effects of stochastic and “hidden” processes on the system-level behavior	This skill requires a question to be asked to identify and consider the effects of hidden processes in a system map. The use of this terminology was beyond the scope of our study.
Identify the multiple variables that influence a given system level behavior	This skill requires a question for participants to identify the variables in their system map and further ask how those variables influence a behavior in their system map. The use of this terminology was beyond the scope of our study.
Examine the relative, potentially nonlinear, effects that multiple identified variables have on a given system-level behavior	This skill is an extension to the skill above. The skill requires a question for participants to identify the nonlinear effects of their identified variables in their system map. The use of this terminology was beyond the scope of our study.
Identify, describe, and create system boundaries	This skill requires a question to be asked to identify, describe, and create system boundaries in a system map. The use of this terminology was beyond the scope of our study.
Consider possible effects of a system’s environment on the system’s behaviors	This skill requires a question to be asked to consider the effects of a system’s environment. The use of this terminology was beyond the scope of our study.

8.2.1.8 S1.8. Scoring method for ST skills

Table S4. Overview of systems thinking skills linked to how sections describing how they are assessed.

Systems Thinking Skill	Alignment with parts in the scoring method
Identify the individual components and processes within a system	Part 1: Concepts
Identify various levels of organization in a system	Part 2: Granularity
Organize components and place them within a framework of relationships	Part 3: Junctions
Think back and forth between different levels of organization in a system	Part 6: Back and forth Thinking

Identify the ways in which components of a system are connected	Part 4: Inward and Outward connections Part 5: Simple connections Part 7: Types of connections – indirect, moderated, and circular Part 15: Modes of Reasoning
Identify behaviors that change over time	Part 8: Behaviors that change over time
Explain and predict how a system has changed and will change over time	Part 9: Predict and explain how a system has/will change over time Part 15: Modes of Reasoning
Use behavior-over-time trends under one set of conditions to make predictions about behavior-over-time trends under another set of conditions	Part 10: Behavior-over-time trends
Identify, examine, and explain (to the extent possible) emergent system-level behaviors	Part 11: Emergent behaviors
Consider the role of human actions on current and future system-level behaviors	Part 12: Impact of human actions
Consider how the system under study might be a component of and contribute to the behaviors of a larger system	Part 13: Component of a larger system Part 14: Connections to different contexts

Part 1: Concepts

- All concepts (components and/or processes) were listed and counted from participants systems before and after the climate simulation
- A concept can be any word or phrase that is connected by lines or arrows

Part 2: Granularity

- All concepts listed were assigned a level of granularity

Table S5. Coding scheme for levels of granularity.

Level	Coding term	Description	Examples
Phenomena/ Global	P	Something that can be observed and exists or happens globally	Climate change, efficiency, global temperature, renewable
Application and examples	A	Applications or examples of phenomena	Modes of transportation, fuel, fertilizer, coal
Chemical application and examples	CA	Applications or examples of phenomena that is chemistry related	CO ₂ emissions, GHG molecules in atmosphere
Chemical processes and properties	CP	Characteristics or behaviors of a chemical/substance that may be observed or chemical processes that chemicals may undergo	exothermic process, heat, atmospheric pressure, gene modification
Molecular	M	Things related to individual compounds or chemical examples	CO ₂ , CH ₄
Atomic	At	Things related to an atom or atoms and examples	hydrogen, calcium, breaking of bonds

Subatomic	s	Things that are smaller than or occurring with an atom	electrons, charges, radioactive particles
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Part 3: Junctions

- For each concept in participants systems (before and after the simulation), **Y** was coded if the concept had a junction, and **N** was coded if the concept did not have a junction
- All Y codes were counted before and after the simulation for analysis

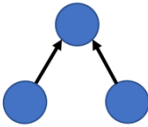
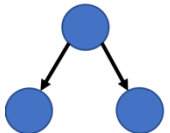
Table S6. Criteria for determining junctions.

Junction	A concept is connected to at least 3 other concepts in any way (for example, it does not matter if there are linking words or not to these other concepts, the direction of arrows does not matter at this point)
No junction	A concept that is connected to two or less concepts

Part 4: Inward and Outward connections

- For each concept in participants systems (before and after the simulation), **Y** was coded if the concept had an inward and/or outward connections and **N** was coded if the concept did not have one of these connections
- All Y codes were counted for inward and outward connections before and after the simulation for analysis

Table S7. Criteria for determining inward and outward connections.

Inward connection		A concept that has two or more arrows pointing towards that concept. Note: The arrow does not need to contain a linking word that relates the two concepts, but the connections must include arrows not lines.
Outward connections		A concept that has two or more arrows pointing away from that concept. Note: The arrow does not need to contain a linking word that relates the two concepts, but the connections must include arrows not lines.

Part 5: Simple connections

- All simple connections were listed from participants systems before and after the climate simulation
- A simple connection was defined as a one line connecting two concepts

Ex. [concept 1] — linking words — [concept 2]

[Fuel for vehicles] undergoes **[combustion in the car engine]**

- Connections were separated into two categories – propositions (includes linking words) and no propositions (only a line)

- All connections with and without propositions were counted before and after the simulation

Table S8. Criteria for determining relationships with and without propositions.

Relationship with proposition	A relationship with a proposition is a connection ONLY between two concepts that have a linking word or phrase accompanied by an arrow.	Example: CO ₂ is one factor responsible for climate change Note: Concepts are bolded, linking words are not bolded
Relationship without proposition	A relationship with a proposition is a connection ONLY between two concepts that DO NOT have a linking word or phrase. An arrow is only present between two concepts.	Example: Better energy sources → efficiency

Part 6: Back and forth Thinking

- For each simple connection present in the participants system (before and after simulation), each concept in the connection was coded for a level of granularity
- The code for each connection includes the level of granularity for the first concept, a dash representing the connection, and the level of granularity for the second concept
- All connections were counted in terms of the levels of granularity

Table S9. Coding scheme for determining levels of granularity within simple connections for connections with and without propositions.

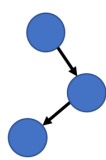
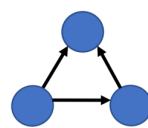
Simple connections	Example	Code
With proposition	Electricity leaves the smallest carbon footprint	P – CA
Without proposition	Gas → CO ₂	A – M

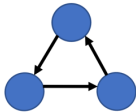
Part 7: Types of connections – indirect, moderated, and circular

- All indirect connections, moderated connections, and circular loops from participants systems before and after the simulation were identified and counted (see definitions and examples in Table S10)

Table S10. Criteria for determining indirect, moderated, and circular connections.

Table S10. Criteria for determining indirect, moderated, and circular connections.

Indirect connection		Concepts are only connected to one another in a linear route.
Moderated connection		Concepts are connected by multiple branches, but the branches are closed by linking back to another concept. There is only one concept as the end point in the connection.

Circular loop		Concepts are connected in a circular route.
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- Any of these types of connections may include a combination of simple connections in Part 5 with or without propositions (linking words)
- When looking these types of connections, the concepts **MUST** be connected by a one headed ARROW - not a single line
- Connections within other connections can be counted

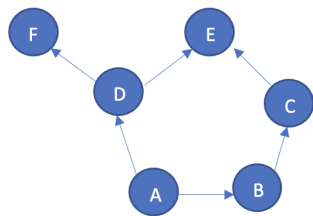


Figure S4. An example of a linear connection ($A \rightarrow D \rightarrow F$) may be part of a closed branching connection ($A \rightarrow B \rightarrow C, D \rightarrow E$).

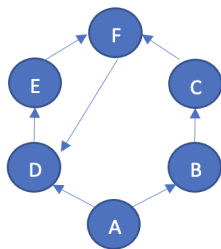
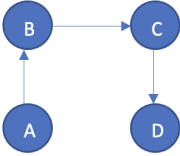
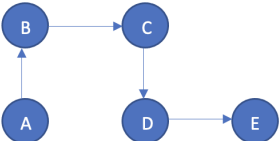
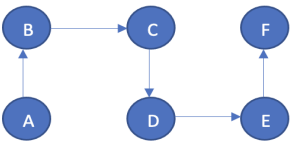
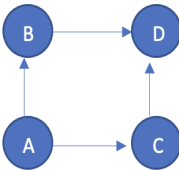
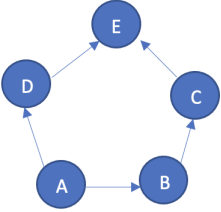
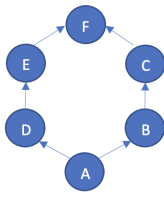
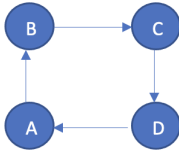
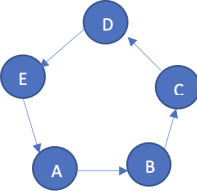
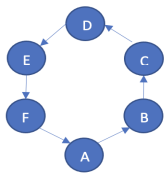


Figure S5. An example of a circular loop ($D \rightarrow E \rightarrow F \rightarrow D$) may be inside a closed branching connection ($A \rightarrow B \rightarrow C, (D \rightarrow E) \rightarrow F$).

- The connections shown in Table S10 are not limited to the length of that type of connection
 - Ex: a linear connection could be 5 concepts long ($A \rightarrow B \rightarrow C \rightarrow D \rightarrow E$) exemplified in Table S11

Table S11. Variations for types of connections along with notation used for coding.

Indirect connection	$A \rightarrow B \rightarrow C \rightarrow D$	$A \rightarrow B \rightarrow C \rightarrow D \rightarrow E$	$A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow F$
			

Moderated connection	$A \rightarrow B, C \rightarrow D$ 	$A \rightarrow B \rightarrow C, D \rightarrow E$ 	$A \rightarrow B \rightarrow C, (D \rightarrow E) \rightarrow F$ 
Circular connection	$A \rightarrow B \rightarrow C \rightarrow D \rightarrow A$ 	$A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow A$ 	$A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow F \rightarrow A$ 

- Moderated connections have the most complex notation
 - a **comma** is used to indicate the last two concepts that are connected to the last concept (arrows are pointing inward to)
 - **brackets** are used in connections bigger than 5 concepts where the brackets are placed around the part of the connection that feeds from the first concept in the other direction

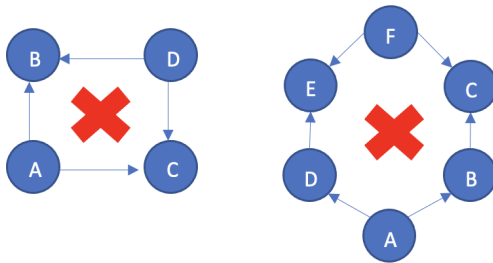


Figure S6. Incorrect examples of moderated connections where there are two concepts as end points.

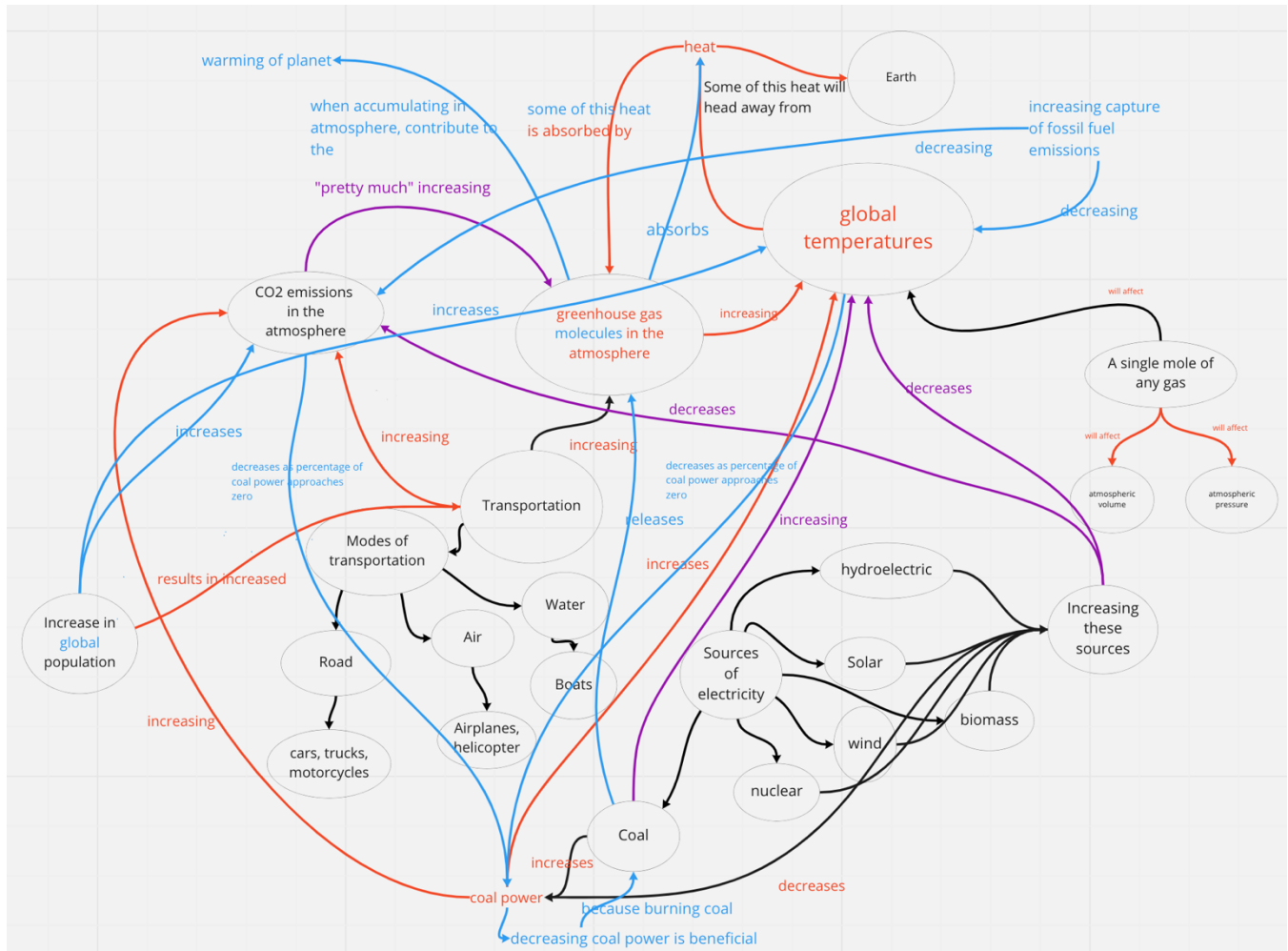


Figure S7. Example of a participants' (P1) system map.

Examples of connections in P1 system map:

Indirect connection: Increase in global population → CO₂ emissions in the atmosphere → coal power

Moderated connection: Increase in global population → transportation, greenhouse gas molecules in the atmosphere → global temperature

Circular connection: coal power → CO₂ emissions in the atmosphere → greenhouse gas molecules in the atmosphere → global temperatures → coal power

Part 8: Behaviors that change over time

- Looked at all data for statements or connections that describe interactions that take place in the future (prediction) or have taken place in the past (retrospection)
- Participants did not need to have "over time" present in statements or connections

Table S12. Examples of statements or connections made by participants that identify behaviors that change over time.

Participant	Example
P3 -after simulation	“Better understanding the way that carbon dioxide behaves on the molecular level is also very important in understanding what changes need to be made to revert the damages that have been done before they are irreversible.”
P5 – before simulation	“Pesticides have been developed over the years to maximize crop yield.”
P10 – after simulation	“Higher population in 2050 leads to greater demand for crude oil.”
P13 – after simulation	“Land use and agriculture are estimated to have contributed 23% to global anthropogenic greenhouse gas emissions from 2007-2016.”

Part 9: Predict and explain how a system has/will change over time

- Assessed in two parts, (1) how students predict system has changed and (2) how students explain system has changed
- We developed three codes for how a student could predict a system has changed.
- No prediction was coded when no answer was provided or some indication that they did not know what to predict
- Partial change was coded when the answer included some concepts and connections being changed while other concepts and connections were unchanged.
- Holistic change was coded when the answer included that all concepts and connections would change

Table S13. Coding scheme with examples for how participants make predictions to how their system changes over time.

Participant	Code	Example
P15	No prediction	“I cannot think of anything that can replace the materials.”
P5	Predicting system partially changed	“It would remove some ideas or topics that are helpful in getting a better understanding of the topic.”
P12	Predicting system holistically changed	“It would almost completely dismantle the connections between everything, because food is central to agriculture.”

Table S14. Coding scheme with examples for how participants explain how their system changes over time.

Participant	Code	Example	Explanation for code
P3	Descriptive	“It would remove most of the web because cars are the first thing that comes to my mind when thinking about transportation optimization.” “Most people use cars to get from place to place. I feel like this is the least niche idea when	The explanation incorporates descriptive properties about the concept being explained.

		it comes to transportation optimization.”	
P9	Relational	“Removing the emissions will mean that we have a better climate in the first place, and we won’t be able to contact global trade...etc.”	The links between emissions, climate and global trade are NOT explained.
P6	Linear Causal	“Without the second idea, there would be no concepts to compare public transport and cars/vehicles. For example, cars/vehicles emit greater CO ₂ in the atmosphere which raises global temperature having a greater influence on climate change.”	Cars/vehicles are invoked to explain the cause-and-effect relationship been individual transportation and climate change - relationship is explained.

Part 10: Behavior-over-time trends

- Looked for responses and connections that included a condition for one concept (e.g., increasing, decreasing) a describing the influence it has for the behavior of another concept (e.g., increasing, decreasing)
- Responses or connections did not need to explicitly mention “over time”

Table S15. Examples of responses and connections that describe behavior over time trends.

Participant	Example
P1 -after simulation	“Increase in global population results in increased CO ₂ emissions in the atmosphere.” “CO ₂ emissions decrease as the percentage of coal power approaches zero.”
P10 – before simulation	“The degradation of the ozone layer leads to the gradual increase in global temperature as more and more UV radiation gets past the ozone layer.”
P14 – after simulation	“Increase forest protection by 50% needs a reforestation rate of 300 thousand km ² /year will help reduce the CO ₂ in atmosphere.”
P17 – before simulation	“Reduce the CO ₂ emissions can ultimately reduce the depletion of ozone layer.”

Part 11: Emergent behaviors

- Participants’ ability to identify emergence was assessed based on their individual responses to the following question, “Identify any similarities and differences between each visual representation.” in task 3 of the ST intervention
- If participants indicated a greater property or behavior of their systems considered together, then their response was coded as emergence identified
- If participants did not indicate a greater property or behavior of their systems considered together, then their response was coded as emergence not identified
- Two participants did not provide any response to this question

Table S16. Coding scheme with examples for identifying emergence.

Participant	Code	Example	Explanation for code
P5	Emergence identified	“In terms of the transportation subject, had very similar points. Workspace 8 had more to do with researching new ways while mine was more about implementing existing ways that are more efficient. We were able to relate agriculture and land use to our topic through the transport of goods efficiently and being conscious of the environment.”	Identified bigger property (i.e., transport of goods efficiently and being conscious of the environment) by emerging both topics - transportation and agriculture.
P7	Emergence not identified	“The visual are similar in a tree branching out form, along with idea that can be grouped together in a hierarchy.”	Explained the similarity of the structure of their systems not the content of their systems.
P1		“Similarities: As population increases, there will be an increase in demand. More shipping (boats and trucks) increasing carbon dioxide emissions. Differences: I focused more on transportation while she focused more on materials.”	Participant only focuses on components of both systems.

Part 12: Impact of human actions

- Here, we looked for connections participants made that describe how human action influences their system
- We considered connections from verbal and written (e.g., systems on Miro or google form) responses

Table S17. Examples of responses and connections that describe human action influencing aspects of participants’ systems.

Participant	Example
P2 -after simulation	“Planet will reach a point where it is unable to produce a sufficient amount of material as a result humans may resort to producing artificial materials using chemistry in hopes to recreate what is found in the natural world.”
P4 – before simulation	“So, I just said that, in the branch of electric cars, we could focus on optimizing manufacturing, we could focus on creating more fuel-efficient batteries, and that’ll have like, give opportunities for engineering and research careers. For gas powered cars. I was thinking that like most we could do is either optimize manufacturing, or optimize the fuel efficiency, which is already pretty good.”
P9 – after simulation	“It triggers the mind to want to think about a solution to this heartbreaking reality, it’s like using graphs and visual

	representations to show the fact that we humans are very selfish and are primarily concerned with ourselves and our momentary world, not bothering to take a glance at the reality of the future generations.
P17 – before simulation	“People's convenience of the shift is a challenge that we may face when trying to implement clean fuel into cars.”
P12 – after simulation	“So, I guess we can be more like, agriculture land should be increasing, but I guess we can reduce emissions by being more efficient, while at the same time supporting the growing population.”

Part 13: Component of a larger system

- Here, we consider climate change to be the larger system of interest as it was overarching topic that formed the five topics (e.g., transportation, land use and agriculture, electricity, materials, and buildings). The five topics were sections of the Design Our Climate simulation that the participants navigated through.
- Therefore, for this skill, we looked for connections participants made to concepts directly related to climate change

Table S18. Examples of responses that describe connections participants made to climate change concepts.

Participant	Example
P1-before simulation	“Greenhouse gas molecules when accumulating in the atmosphere contribute to the warming of the planet.”
P4 – after simulation	“Most impactful choice we can do to stop climate change is to drive less and carpool more often.”
P17 – before simulation	“Switch to clean fuel would overall reduce climate change.”
P13 – after simulation	“Land use and agriculture are estimated to have contributed 23% to global anthropogenic greenhouse gas emissions from 2007-2016.”

Part 14: Connections to different contexts

- We could not assess participants' abilities to identify boundaries of their system as we did not specifically ask participants to perform that task
- Therefore, we used the Environmental and Sustainability triangular model to identify different contexts where participants made connections
- Contexts include, individual, societal, nature along with their connections to each other and to chemistry
- Definitions of each can be found in the **8.2.1.3** S1.3. Theoretical Framework section
- Connections to these contexts contribute towards the breadth of connections that participants demonstrated which can lead to the demonstration of other ST skills (e.g., the identification of boundaries and consideration of the system as part of a larger system)

Table S19. Coding scheme of participants' connections made to different contexts.

Participant	Code	Example
P11 – after simulation	Individual	“One cannot relegate the efficiency of one resource to zero.”

P2 – before simulation	Society	“Overexploitation is a result of increased demands for a certain product”
P1 – before simulation	Nature	“Greenhouse gases from the atmosphere increase global temperatures.”
P3 – after simulation	Individual and societal	“Average consumption of all types of energy per year leads to more travel in groups.”
P2 – after simulation	Individual and nature	“Planet will reach a point where it is unable to produce a sufficient amount of material as a result humans may resort to producing artificial materials using chemistry in hopes to recreate what is found in the natural world.”
P6 – after simulation	Societal and environmental	“Public transport/carpool decreases the emission of CO ₂ emissions.”
	Individual and chemistry	N.A.
P10 – after simulation	Societal and chemistry	“More demand for vehicles we can use carbon capture devices.”
P6 – after simulation	Nature and chemistry	“CO ₂ is the major greenhouse gas concentration of 280 to 412 ppm in 2019.”

Part 15: Modes of Reasoning

- We used the modes of reasoning framework to understand how students explain connections in their systems and how students explain how their system changes over time
- There are four modes of reasoning present in the framework; however, we only have evidence of three modes of reasoning from students’ explanations.
- For more examples and in-depth explanations of the four types of modes of reasoning, refer to the following papers:^{48–50}

Table S18. Coding scheme for modes of reasoning used by participants.

Participant	Code	Example	Explanation for code
P2	Descriptive	“Chemistry relates to the topic of choice because materials obtained from mining consist of various elements. These elements could either be used as is or undergo a series of chemical reactions to produce something new.”	No cause-and-effect relationship.
P12	Relational	“The process of seeds growing into plants and animals eating plants can be explained by biochemistry. Plants take nutrients from the soil and animals get their nutrients from plants.”	The link between the process of seed growing and biochemistry is not explained.
P1	Linear Causal	“Greenhouse gases absorb heat. Some of this heat will	Heat is invoked to explain the cause-and-

		head away from Earth while some of the heat is absorbed by other green house has molecules. These molecules contribute to the warming of the planet as they accumulate in the atmosphere. “	effect relationship been greenhouse gases and warming of the planet. Relationship is explained.
No participants demonstrated	Multicomponent Causal	“Humans are causing global warming because they generate CO ₂ from burning fossil fuels. CO ₂ is a greenhouse gas that contributes to global warming by trapping heat in the Earth’s atmosphere. In addition, humans participate in agricultural activities that increase CH ₄ generation, another greenhouse gas that traps heat in the Earth’s atmosphere.” ⁴⁸	Multiple pieces of evidence are used to explain the link between humans and global warming. There is an added chain of causal reasoning to explain the ways that contribute to global warming. ⁴⁸

8.2.2 S2. Results and Discussion

8.2.2.1 S2.1. Additional information for RQ1: What ST skills does undergraduate chemistry students use without scaffolding to construct system maps?

System as a whole (blue, Figure 6): Researchers from different disciplines have previously identified that one cannot understand a system without identifying its components and that identifying components serves as a prerequisite for developing more high-order ST skills.^{16,21,43,52} Our finding is relatively positive; however, making comparisons with our findings and other ST studies is a challenge. We did not look at the quality of components related to the topic on climate change while other studies have looked for students’ ability to identify specific components of a system which adds an extra element to how this skill is assessed.¹⁶ Therefore, future research will need to explore the correctness of concepts and relationships in a system that focuses on a chemistry topic.

Interconnections (orange, Figure 6): Learners first need to acquire an understanding of the components of the system to identify relevant connections between these components.^{15,16} Unsurprisingly, all participants identified connections, considering they all identified components and were prompted to make connections between the components. A prompt for

making connections was explicitly used in our study as we felt it was necessary to allow all participants equal opportunity to demonstrate this skill. This is because participants were specifically asked to make a visual representation, purposefully refraining from using systems related terminology (e.g., systems map, concept map) in the study.

Emergent behaviors (green, Figure 6): An understanding of emergence is critical for understanding scientific phenomena; however, identifying emergence can be challenging when a learner does not have much experience thinking in this way. The language through which basic concepts in chemistry are discussed does not generally include emergence.^{42,60} Therefore, we assumed participants had no prior knowledge on ST and prompted participants by asking them to “identify any similarities and differences between each system map” in the group task (task 3). Eight participants did and eight participants did not identify emergence when considering similarities and differences of system maps. There was insufficient information to assess the remaining two participants’ data. One participant did not participate in task 3, and the other participant provided a response that did not provide us with enough information for assessment.

The nature of collaboration in the third ST task might have facilitated participants ability to identify emergence since some participants had identified greater properties of their system maps only during the third ST task. However, we do not have enough evidence to identify if the type of question asked or the nature of the conversations helped participants identify emergence. Therefore, future analyses are needed to explore how collaboration might impact the system maps created.

8.2.2.2 S2.2. Additional theme: More time to engage in systems thinking tasks and engagement with a simulation enhances systems thinking skills

Participants demonstrate certain ST skills more after engaging with the DOC simulation (Figure S8, Figure S9, and Figure S10). We looked at the extent that participants demonstrated ST skills before and after engaging with DOC simulation. Two factors may have influenced this finding which were time to add onto their systems and engaging with the simulation. We

cannot conclude which factor had a greater influence on participants' abilities to demonstrate ST skills as added time and engagement with the simulation occurred simultaneously.

We assessed the following skills before and after engaging with simulation; identify and organize components, identify levels of organization, identify connections, identify behaviors that change over time, predict how one variable influences another variable, consider the role of human action on the system, and consider how the system contributes to a larger system. Figure S8 shows participants' systems include more concepts, junctions, and connections after engaging with the DOC simulation. In general, participants' systems have expanded and include more interconnections. We also looked at how additional time and/or the DOC simulation impacted the types of connections made in participants' systems (Figure S9). Circular loops were previously identified as a connection that was not commonly seen in participants' system maps. In addition, there was not a large increase in this type of connection compared to the others after engaging with the simulation. Additional time nor engagement with the simulation helped to elicit this connection, emphasizing the need to explicitly teach circular loops in chemistry courses. Figure S10 shows a relatively large increase for the number of participants who demonstrated skills related to behaviors over time after the simulation. Again, we cannot conclude if any factors impacted this finding, whether having extra time to think about behaviors or being introduced to behavior over time connections in the simulation resulted in more participants demonstrating these skills. While we cannot conclude why a smaller increase was shown for participants demonstrating ST skills related to boundaries, the finding is positive as more participants demonstrated these skills with more time and/or engagement with the simulation. More research will need to explore these factors more deeply so that educators can understand the supports that can effectively help students demonstrate ST skills.

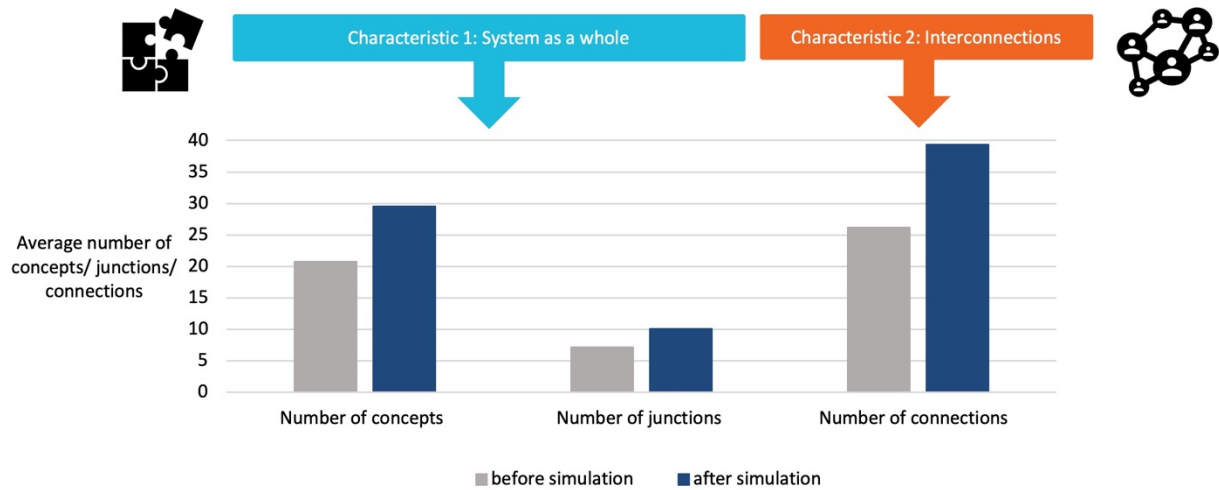


Figure S8. The average number of concepts, junctions, and connections in participants' systems before and after engaging with the simulation.

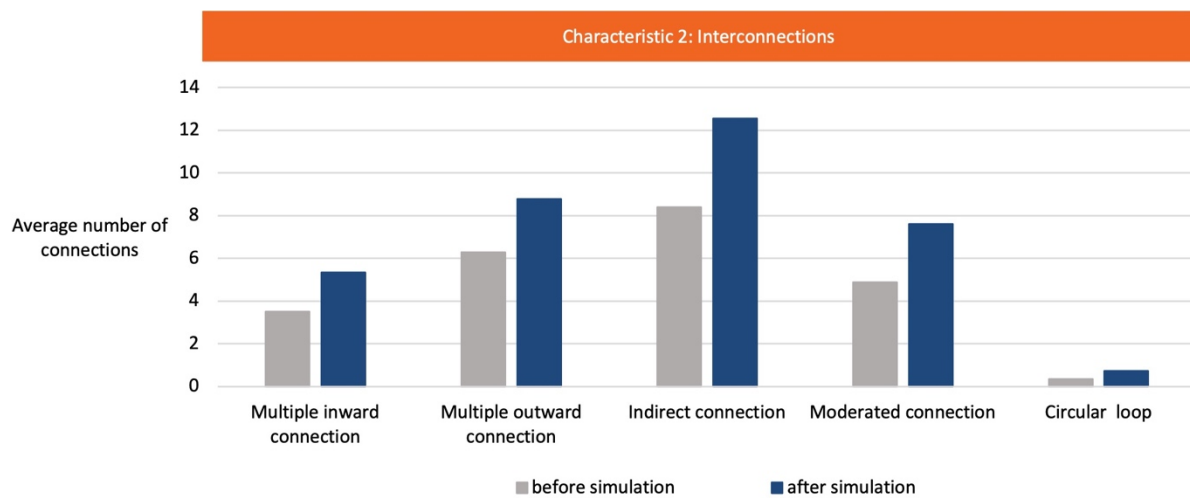


Figure S9. The average number of the types of connections in participants' systems before and after engaging with the DOC simulation.

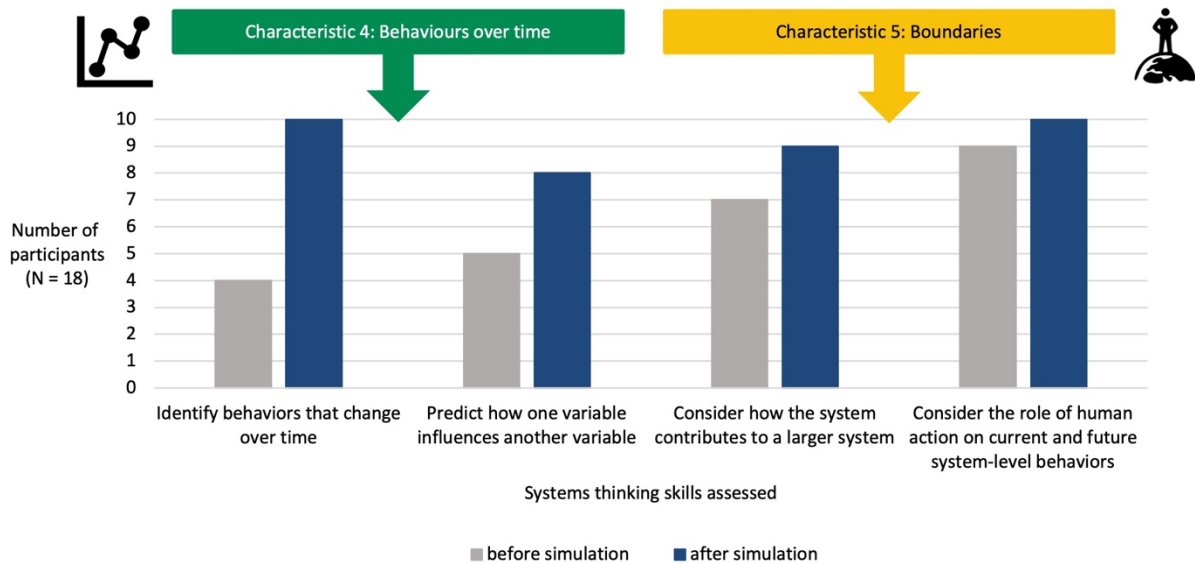


Figure S10. Number of participants who demonstrate behaviors over time skills and skills related to boundaries.

8.2.3 S3. Systems Thinking Intervention

8.2.3.1 S3.1. Task 1

1. Choose a topic of your choice that you want to investigate. *

- ☐ Electricity
- ☐ Materials
- ☐ Buildings
- ☐ Land Use/Agriculture
- ☐ Transportation

2. List as many ideas/concepts (e.g., objects, phenomena, processes, behaviours etc.) in one word or phrase that may relate to your topic of choice and/or personal experience. *

Long answer text

3. Using the following link (<https://miro.com/>) and the features provided in Miro, create a visual representation (e.g., a diagram, concept map, illustration/graphic etc.) of interconnected relationships between the ideas/concepts from question 2.

4. Use your chemistry knowledge to incorporate chemistry concepts into your visual representation. Please include different levels of granularity. For example, focus on things that are visible and touchable as well as focus on the molecular level (molecules themselves)

Description (optional)

5a. Imagine that you remove the second idea/concept listed in question 2. How does removing the second idea/concept impact the rest of your visual representation? *

Long answer text

5b. Why does removing the second idea/concept impact the rest of your visual representation? *

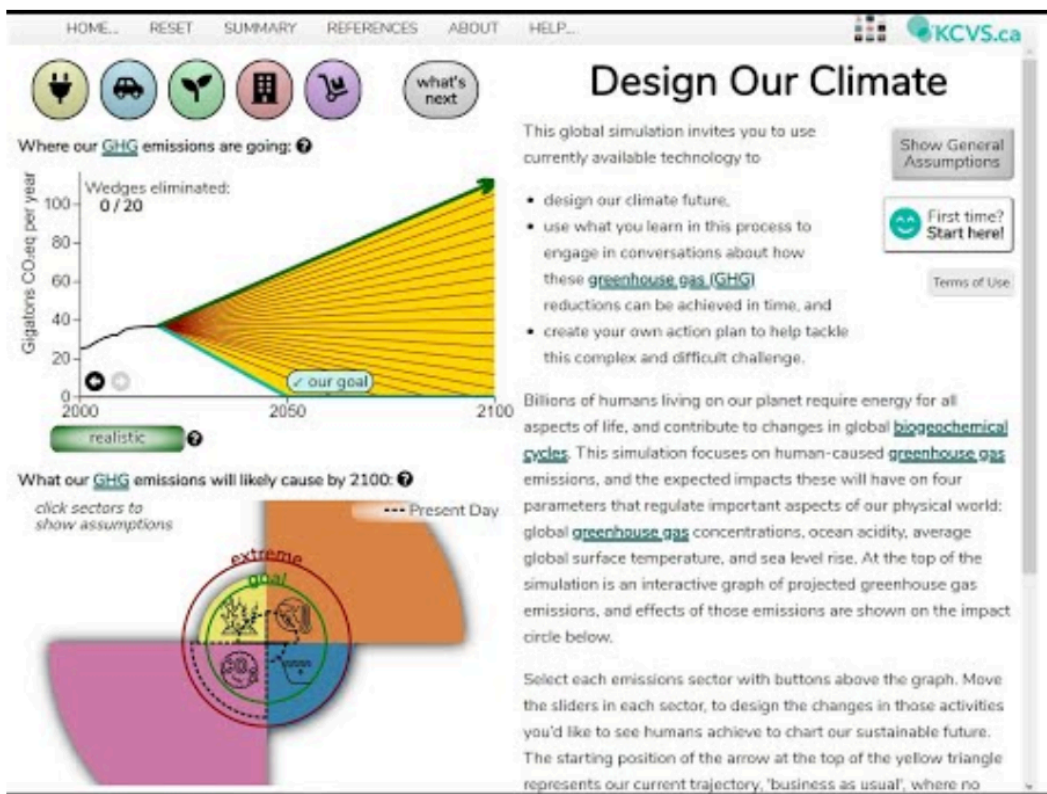
Long answer text

8.2.3.2 S3.2. Task 2

1. Please take 5 minutes to explore the Design Our Climate (DOC) simulation (https://applets.kcvs.ca/DesignOurClimate/DesignOurClimateSim.html) on your own and write down any relevant information for your visual representation in the space provided below. *

Long answer text

2. Please watch a short 3-minute DOC introduction video on how to navigate through the DOC simulation

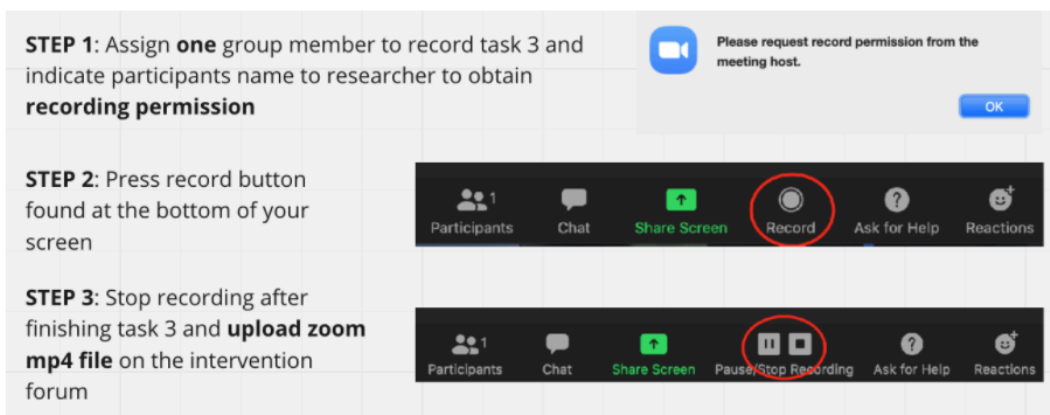


3. Continue to explore the simulation and write down any relevant information while using the simulation in the space provided below. Additionally, continue to include make connections to chemistry. Use this information to expand your visual representation as much as possible. You can refer back to the DOC simulation as needed when expanding your visual representation.

Long answer text

8.2.3.3 S3.3. Task 3

1. You will now be placed in a group of 2 or 3 people in Miro. Please assign one person in your group to record your group conversation using the zoom recording feature in your breakout room. At the end of task 3 upload the recording in question 6 (below).



2. Please share your visual representation with each group member (each group member will explain their visual representation in ~2 minutes).

Link to Miro:

3. Please answer the following question individually. Identify any similarities and differences between each visual representation. Please write your response in the space below. *

Long answer text

4. Find a way to connect each visual representation into one larger visual representation on Miro.

Description (optional)

5. Please discuss the following question in your group. What is different about the visual representation that you made through discussions than just setting your individual systems side by side?

Description (optional)

8.2.4 S4. References

- (1) Xu, X.; Lewis, J. E. Refinement of a Chemistry Attitude Measure for College Students. *J. Chem. Educ.* **2011**, 88 (5), 561–568. <https://doi.org/10.1021/ed900071q>.
- (2) Schunk, D. H. *Learning Theories: An Educational Perspective (6th Edition)*; Pearson Education Inc: Boston, MA, 2012; Vol. 5.

- (3) 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>.
- (4) 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>.
- (5) Ausubel, D. P.; Novak, J. D.; Hanesian, H. *Educational Psychology: A Cognitive View*, 2nd ed.; New York (N.Y.) : Holt, 1968.
- (6) Galloway, K. R.; Bretz, S. L. Using Cluster Analysis to Characterize Meaningful Learning in a First-Year University Chemistry Laboratory Course. *Chem Educ Res Pr.* **2015**, 16 (4), 879–892. <https://doi.org/10.1039/C5RP00077G>.
- (7) Cobb, P. Where Is the Mind? Constructivist and Sociocultural Perspectives on Mathematical Development. *Educ. Res.* **1994**, 23 (7), 13–20.
<https://doi.org/10.3102/0013189X023007013>.
- (8) 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>.
- (9) 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>.
- (10) Novak, J. D.; Gowin, D. B. *Learning How to Learn*; Cambridge University Press: Cambridge, New York, 1984.
- (11) Luisi, P. Emergence in Chemistry: Chemistry as the Embodiment of Emergence. *Found. Chem.* **2002**, 4, 183–200. <https://doi.org/10.1023/A:1020672005348>.
- (12) van Mil, M. H. W.; Boerwinkel, D. J.; Waarlo, A. J. Modelling Molecular Mechanisms: A Framework of Scientific Reasoning to Construct Molecular-Level Explanations for Cellular Behaviour. *Sci. Educ.* **2013**, 22 (1), 93–118. <https://doi.org/10.1007/s11191-011-9379-7>.
- (13) Talanquer, V. Progressions in Reasoning about Structure–Property Relationships. *Chem. Educ. Res. Pract.* **2018**, 19 (4), 998–1009. <https://doi.org/10.1039/C7RP00187H>.
- (14) Southard, K. M.; Espindola, M. R.; Zaepfel, S. D.; Bolger, M. S. Generative Mechanistic Explanation Building in Undergraduate Molecular and Cellular Biology. *Int. J. Sci. Educ.* **2017**, 39 (13), 1795–1829. <https://doi.org/10.1080/09500693.2017.1353713>.
- (15) 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>.

- (16) 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>.
- (17) 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>.
- (18) Ho, F. M. Turning Challenges into Opportunities for Promoting Systems Thinking through Chemistry Education. *J. Chem. Educ.* **2019**, *96* (12), 2764–2776.
<https://doi.org/10.1021/acs.jchemed.9b00309>.
- (19) Talanquer, V. Some Insights into Assessing Chemical Systems Thinking. *J. Chem. Educ.* **2019**, *96* (12), 2918–2925. <https://doi.org/10.1021/acs.jchemed.9b00218>.
- (20) Richmond, B. Systems Thinking: Critical Thinking Skills for the 1990s and Beyond. *Syst. Dyn. Rev.* **1993**, *9* (2), 113–133. <https://doi.org/10.1002/sdr.4260090203>.
- (21) Orgill, M.; York, S.; MacKellar, J. Introduction to Systems Thinking for the Chemistry Education Community. *J. Chem. Educ.* **2019**, *96* (12), 2720–2729.
<https://doi.org/10.1021/acs.jchemed.9b00169>.
- (22) Sternäng, L.; Lundholm, C. Climate Change and Costs: Investigating Students' Reasoning on Nature and Economic Development. *Environ. Educ. Res.* **2012**, *18* (3), 417–436. <https://doi.org/10.1080/13504622.2011.630532>.
- (23) 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.
- (24) Lincoln, Y. S.; Guba, E. G. *Naturalistic Inquiry*; Sage Publications: Beverly Hills, Calif, 1985.
- (25) 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>3.0.CO;2-T](https://doi.org/10.1002/1520-6858(200033)3:3<163::AID-SYS5>3.0.CO;2-T).
- (26) Frank, M.; Waks, S. Engineering Systems Thinking: A Multifunctional Definition. *Syst. Pract. Action Res.* **2001**, *14* (3), 361–379. <https://doi.org/10.1023/A:1011363516269>.
- (27) Frank, M. What Is “Engineering Systems Thinking”? *Kybernetes* **2002**, *31* (9/10), 1350–1360. <https://doi.org/10.1108/03684920210443554>.
- (28) Frank, M. Knowledge, Abilities, Cognitive Characteristics and Behavioral Competences of Engineers with High Capacity for Engineering Systems Thinking (CEST). *Syst. Eng.* **2006**, *9* (2), 91–103. <https://doi.org/10.1002/sys.20048>.
- (29) Frank, M. Engineering Systems Thinking: Cognitive Competencies of Successful Systems Engineers. *Procedia Comput. Sci.* **2012**, *8*, 273–278.
<https://doi.org/10.1016/j.procs.2012.01.057>.
- (30) Camelia, F.; Ferris, T. L. J.; Cropley, D. H. Development and Initial Validation of an Instrument to Measure Students' Learning About Systems Thinking: The Affective

- Domain. *IEEE Syst. J.* **2018**, 12 (1), 115–124.
<https://doi.org/10.1109/JSYST.2015.2488022>.
- (31) Constable, D. J. C.; Jiménez-González, C.; Matlin, S. A. Navigating Complexity Using Systems Thinking in Chemistry, with Implications for Chemistry Education. *J. Chem. Educ.* **2019**, 96 (12), 2689–2699. <https://doi.org/10.1021/acs.jchemed.9b00368>.
 - (32) 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>.
 - (33) Verhoeff, R. P.; Waarlo, A. J.; Boersma, K. Th. Systems Modelling and the Development of Coherent Understanding of Cell Biology. *Int. J. Sci. Educ.* **2008**, 30 (4), 543–568.
<https://doi.org/10.1080/09500690701237780>.
 - (34) Verhoeff, R. P.; Boersma, K. T.; Waarlo, A. J. Multiple Representations in Modeling Strategies for the Development of Systems Thinking in Biology Education. In *Multiple Representations in Biological Education*; Treagust, D. F., Tsui, C.-Y., Eds.; Springer Netherlands: Dordrecht, 2013; pp 331–348. https://doi.org/10.1007/978-94-007-4192-8_18.
 - (35) 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>.
 - (36) Calhoun, J. G.; Ramiah, K.; Weist, E. M.; Shortell, S. M. Development of a Core Competency Model for the Master of Public Health Degree. *Am. J. Public Health* **2008**, 98 (9), 1598–1607. <https://doi.org/10.2105/AJPH.2007.117978>.
 - (37) Boersma, K.; Waarlo, A. J.; Klaassen, K. The Feasibility of Systems Thinking in Biology Education. *J. Biol. Educ.* **2011**, 45 (4), 190–197.
<https://doi.org/10.1080/00219266.2011.627139>.
 - (38) Arnold, R. D.; Wade, J. P. A Definition of Systems Thinking: A Systems Approach. *Procedia Comput. Sci.* **2015**, 44, 669–678. <https://doi.org/10.1016/j.procs.2015.03.050>.
 - (39) Samon, S.; Levy, S. T. Interactions between Reasoning about Complex Systems and Conceptual Understanding in Learning Chemistry. *J. Res. Sci. Teach.* **2020**, 57 (1), 58–86. <https://doi.org/10.1002/tea.21585>.
 - (40) Verhoeff, R. P. Towards Systems Thinking in Cell Biology Education, Centrum voor Didactiek van Wiskunde en Natuurwetenschappen, Universiteit Utrecht, Utrecht, 2003.
 - (41) Raycroft, M.; Flynn, A. What Works? What's Missing? An Evaluation Model for Science Curricula That Analyses Learning Outcomes through Five Lenses. *Chem. Educ. Res. Pract.* **2020**, 21. <https://doi.org/10.1039/C9RP00157C>.

- (42) Gilbert, L. A.; Gross, D. S.; Kreutz, K. J. Developing Undergraduate Students' Systems Thinking Skills with an InTeGrate Module. *J. Geosci. Educ.* **2019**, 67 (1), 34–49. <https://doi.org/10.1080/10899995.2018.1529469>.
- (43) Hopper, M.; Stave, K. A. Assessing the Effectiveness of Systems Thinking Interventions in the Classroom; 2008; p 26.
- (44) Kopainsky, B.; Alessi, S. M.; Davidsen, P. I. Measuring Knowledge Acquisition in Dynamic Decision Making Tasks; Albany, NY, 2011; pp 1–31.
- (45) Froyd, J.; Pchenitchnaia, L.; Fowler, D.; Simpson, N. Systems Thinking And Integrative Learning Outcomes Paper; Honolulu, Hawaii, 2007. <https://doi.org/10.18260/1-2--1614>.
- (46) Gilissen, M. G. R.; Knippels, M.-C. P. J.; van Joolingen, W. R. Bringing Systems Thinking into the Classroom. *Int. J. Sci. Educ.* **2020**, 42 (8), 1253–1280. <https://doi.org/10.1080/09500693.2020.1755741>.
- (47) Eaton, A. C.; Delaney, S.; Schultz, M. Situating Sustainable Development within Secondary Chemistry Education via Systems Thinking: A Depth Study Approach. *J. Chem. Educ.* **2019**, 96 (12), 2968–2974. <https://doi.org/10.1021/acs.jchemed.9b00266>.
- (48) Squires, A.; Wade, J. P.; Dominick, P.; Gelosh, D. Building a Competency Taxonomy to Guide Experience Acceleration of Lead Program Systems Engineers; STEVENS INST OF TECH HOBOKEN NJ SCHOOL OF SYSTEMS AND ENTERPRISES: Redondo Beach, CA, 2011.
- (49) 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>.
- (50) Sevian, H.; Talanquer, V. Rethinking Chemistry: A Learning Progression on Chemical Thinking. *Chem Educ Res Pr.* **2014**, 15 (1), 10–23. <https://doi.org/10.1039/C3RP00111C>.
- (51) 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>.
- (52) Kali, Y.; Orion, N.; Eylon, B.-S. Effect of Knowledge Integration Activities on Students' Perception of the Earth's Crust as a Cyclic System. *J. Res. Sci. Teach.* **2003**, 40 (6), 545–565. <https://doi.org/10.1002/tea.10096>.
- (53) Wilensky, U.; Resnick, M. Thinking in Levels: A Dynamic Systems Approach to Making Sense of the World. *Journal of Science Education and Technology* **1999**, 8, 3–19. <https://doi.org/10.1023/A:1009421303064>.

8.3 Appendix 3: Supporting Information for Chapter 4

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

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8.3.1 S1. Methods

8.3.1.1 S1.1 Context and Participants

Twenty-four participants completed a demographic survey (n = 17 undergraduate students and n = 7 graduate students). The 17 undergraduate participants came from a range of academic stages (9 first year, 7 second year, one third year) and declared majors including: Biomedical Science, Biopharmaceutical Science, Health Science, Biochemistry, Chemistry, Human Kinetics, Biotechnology, and Biology. The seven graduate participants also reported to be at different academic stages (4 MSc, 2 PhD, 1 Research Associate). Of the 24 participants, our sample was predominately women (19 women, five men) and diverse, reporting to identify with the following groups: 4 Asian – East (e.g., Chinese, Japanese, Korean), 3 Asian – South (e.g., Indian, Pakistani, Sri Lankan), 3 Asian – South East (e.g., Malaysian, Filipino, Vietnamese), 1 Black – African (e.g., Ghanaian, Kenyan, Somali), 4 Latinx/Hispanic (e.g. Argentinean, Chilean, Salvadoran), 1 Middle Eastern (e.g., Egyptian, Iranian, Lebanese), 4 White – European (e.g., Egyptian, Italian, Portuguese, Russian), 6 White – North American (e.g., Canadian, American), and two preferred not to answer.

8.3.1.2 S1.2 Instrument and procedure for data collection

Due to the pandemic, data collection for this study took place entirely through online platforms (i.e., Zoom, Miro, and Google Forms). Each iteration of the intervention allowed up to

eight students to participate, and we conducted the intervention via Zoom, a video conferencing software that allows one or more parties to meet virtually.

Cognitive and affective instruments: The cognitive and affective instruments used for this study were the Attitude towards the Subject of Chemical Inventory version 2 (ASCI. v2)¹ to assess attitudes towards chemistry and a Climate change awareness survey to assess student perceptions on climate change. These instruments were repeated to see how the learning experience influenced their affective domain and knowledge construction. From initial data analyses, we found no significant difference between pre- and post-test data. This data did not add anything to our findings and was not included in this manuscript.

Group Task protocol: In the first prompt, we asked participants to share their system map with their group members. Next, we asked participants to find a way to connect each system map into a new visual representation. After constructing their group system map, we asked participants to discuss, "What is different about the system map that you made through discussions than just setting your individual system maps side by side?" Four of the ten groups did not answer this last question as they either ran out of time or chose not to answer.

8.3.1.3 S1.3 Data analysis details

First, we transcribed the audio files from the interviews and group recordings (Task 3) verbatim. Two researchers, ARS and ZL, read the transcripts to situate themselves with the data and wrote memos on patterns uncovered from the data. Next, ARS coded the interview and group task transcript data line-by-line via open coding, while ZL completed the same procedure for the post-activity ST responses. Open coding allows researchers to break up the data and label it with codes to enable continuous comparison and contrast of similar events in the data, engaging in constant comparative analysis. Then, ARS and ZL proceeded with axial coding by connecting these initial codes and grouping them to form smaller categories. Both 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, ARS created a coding scheme for student experience codes (RQ1), and ZL created a coding scheme for student

perspective codes (RQ2). For the student experiences analysis, we analyzed some of the transcript data (i.e., students explaining how they constructed their system maps) using a slightly different approach as we needed to compare text to visual (i.e., system maps) data. Specifically, after transcribing and coding group task recording data, we created summaries of the initial codes for each participant and group constructing their system maps. These summaries contained the specific order of events that were described by the participants and allowed us to identify similarities and differences of participants' approaches for organizing concepts in their system maps. We compared the summaries of participants' verbal explanations of constructing their system maps to the system map they constructed to identify the consistency of visual representation data and corresponding verbal explanations. We uncovered additional findings from these comparisons.

Following the development of both coding schemes, we critically discussed each scheme with each other and other research group members to clarify definitions of codes and themes. After discussions, we refined the coding schemes, applied the revised coding scheme to the data, and again discussed them amongst the researchers until we reached a consensus. The final coding schemes are presented in S2. Throughout, writing memos helped communicate the coding process and emerging patterns, categories, and themes in the data among the researchers.² The record of memos helped ensure confirmability and dependability of the analysis.³ We created labels for each participant (e.g., U1 represents undergraduate student 1 and G1 represents graduate student 1) to keep anonymity of participants identities which are used to communicate this research. Additionally, we removed unnecessary words (e.g., umm, like) or repeated words from quotes to improve its readability.

8.3.1.4 S1.4 Theoretical Framework

Modern Information Processing Theory. This theory guided our research by understanding how learners can 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. The first task required learners to use their prior knowledge to construct a system map. The second task allowed new information to be presented to the learner in a

meaningful manner by linking new concepts to the learners' prior knowledge to potentially expand their system map. The third task altered the learning environment (i.e., collaborative setting) to allow learners to link new concepts in a different way.

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. Students with well-organized knowledge structures from their long-term memory may hold more information in their working memories due to their ability to chunk (i.e., group) this knowledge and consolidate new information from having more experience using this knowledge.⁴ Students with less organized knowledge structures may have less experience consolidating information in the working memory; for them, new information may not seem relevant or be considered.⁴

Socio-cultural Theory. Sociocultural theory explains how the learning environment plays an integral role in cognition.^{5,6} This theory stresses the importance of culture and social interaction in developing and shaping individuals, with an essential application being peer collaboration.⁶⁻⁸ Interactions with other individuals in the learning environment stimulate developmental processes and foster cognitive growth.⁶ Cognitive development occurs in the zone of proximal development (ZPD, differentiating between what a learner can do individually and what they can do when assisted by others),^{46,47,52} because ZPD reflects that collaboration with more capable peers will share that knowledge and skill with less knowledgeable peers to accomplish a task.^{6,9}

8.3.1.5 S1.5 Validity Evidence

We addressed the validity of the findings using well-established methods such as 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.¹⁰⁻¹²

Content validity was performed before data collection to assess the quality of responses to questions and activities in the ST intervention. Here, two experts who research STICE engaged in the ST intervention and provided comments to improve the questions in the ST

tasks. Additionally, we collected validity evidence based on response process to ensure the participants' thought processes aligned with what we intended to ask when answering the questions.¹³ A pilot of the ST invention was conducted with four chemistry graduate students and two undergraduate chemistry students, as these students represented the appropriate group of participants for this study. Additionally, two students completed interviews to provide feedback on the ST interview questions and obtain their thought processes when answering the questions. We acknowledged all comments and feedback and made changes to items accordingly.

Triangulation was another method used prior to data collection. This validity procedure involved us converging multiple and different sources of information to form themes in a study. We incorporated triangulation into our research design by using numerous methods to collect evidence on how students demonstrate ST skills (e.g., visualizations, google form, audio, and screen recordings). The validity evidence of the findings was established by relying on multiple forms of evidence instead of a single data point in the study.

In addition to collecting validity evidence during the study's design, we took steps throughout data analysis to maximize the findings' trustworthiness. Disconfirming evidence is one method we used that involves searching through the data for evidence that disconfirms preliminary themes. For example, we found positive findings on participants' perspectives toward ST. Therefore, Z.L. sifted through other data sources from the ST intervention and interviews, looking for negative perspectives that would disconfirm our findings. While we found no explicitly negative perspectives, we found neither negative nor positive responses; this data is shared in the manuscript.

We used peer debriefing throughout the study. Regular sessions between the researchers and members of the Flynn Research Group allowed members to ask in-depth questions about the methods and interpretations. They helped address any assumptions and/or biases in the analysis. This process maximized the credibility of the results.¹⁰

Lastly, we describe the setting, the participants, and the themes of this qualitative study in rich detail. Thus, the credibility of the findings is established through the lens of the

reader, who can interpret the narrative and setting of the study.¹² Full transcripts are not provided to preserve participants' anonymity.

8.3.2 S2. Codebooks

8.3.2.1 S2.1 Student experiences codebook

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

Theme 1: While collaborating, participants had beneficial and challenging experiences constructing system maps		
Category	Codes and description	Exemplar quotes
Beneficial experiences constructing system maps collaboratively	Recognized and appreciated the difference of perspectives and ideas from group members:	“Interviewer: What new perspectives did you have about climate change and/or chemistry when collaborating with your group? If any?” U9: “Definitely the political perspective, I never actually looked at it that way on the political side of it.”
	Participants mentioned they gained a new perspective or ideas about a problem from their group member(s).	U12: “The group one is mostly better, because... it combines all our ideas, obviously...individually, you won't come up with the same ideas as another person, even though like, like two of us did the same topic of agriculture. There were still things that we added to each other ...”
	Participants mention the group system map is better because it combines all ideas from all group members since people have different ways of thinking about a topic.	U3: “It was nice to share ideas, me and one of my other group mates had the same topic. ... Like one thing I think he mentioned that I didn't was about, like research into different fuel cells.”
		G2: “Well, I'm not fully certain of what the new ideas I gained thru this, I certainly gained new ideas. ... 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, easily, much more easily.” From group task (Task 3): “U14: Okay. So, I mean, I think that's when I see a lot more connections between everything. I think I would have liked to connect, like electricity and agriculture together more. But I think time constraints that would have taken a lot more time. But I, I like this, what we have because it's very connected. And you can see like cause-and-effect kind of stuff.

U11: Yeah, there's a more unified sort of feel because you can see the different aspects of climate change and chemistry, respectively. So, it's kind of interesting. And the whole idea of problems and solutions also kind of adds a sense of duality to the issue.

U14: Yeah.

U11: Yeah, I think it's a lot more organized.

U14: Yeah.

U12: Yeah, for sure. Like for the individual ones. I think we just started with like, a bunch of big words or concepts thrown onto the page, and then just making random connections in between.

U11: Yeah. Very chaotically.

U14: Yeah, I think this made it a lot easier to like, organize your thoughts and like, especially having like, I mean I know for electricity you didn't, but for like having two diagrams to base the information off of was really helpful, because you could think about things that you didn't like, think about at first.

U11: Yeah, different perspectives on the same issue, and that's always helpful."

Group system map brings more aspects together and gives a more well-rounded

view: Participants mention that they liked the group system map more than their individual system map because combining ideas and concepts brought aspects more together to give a more well-rounded view of topics, including finding one solution to the multiple problems addressed.

G4: "The group created one, I definitely like that one, because I think what I always had trouble with when learning chemistry was that ... I always found it kind of frustrating just looking at like, isolated reactions... But then also, when it came to just biology, I was kind of frustrated with like, not knowing the details of it, I was kind of like, okay, that happens. But why. So, I think I liked the two group together maps, because I think it did kind of bring them together more...And then I think it also kind of helps to...like I said, with the transport trucks coming in, ...it kind of gave another view that I just like hadn't considered before ... And so, when, when that came in, it's kind of like added another layer to what I had. And I think it just kind of gave an overall more well-rounded picture of the thing when you had it coming from both sides."

G1: "I think the group created one because ... it looks at two problems ... and tries to like tie them together and make one solution. While each individual visual ... representation... only looks at one specific problem, while the group one really like tried to take two problems and try to have one common solution that would help both.

G1: "Well, I think when you discuss more in a group, you expand more. It's kind of like a domino effect. How like one thing can impact another, and then impact another, and impact another. Hmm. So, like overall, I think that maybe you see you change a little something in one aspect that like you can still. That would change something else. And like, kind of like you always want

to think of everything. Kind like all things that you would affect it.”

U10: “I like your idea, especially the whole carbon footprint thing. I'm liking how you've interconnected everything. Because when I only looked at transports but now based off of what you've done in your visualization, I think we can incorporate what you've talked about in terms of industries, waste, material, and electricity, and also the water I have for transport. We bring all of that together now to make like a whole visualization that talks about everything. Because when you start talking about industries, for me, the first thing I thought about for industries is the industries that refine the fuel.”

Group system map construction is more meaningful:

Participants think the group system map is better because it contains more meaningful concepts. Additionally, participants mention that combining system maps makes a product that matters and provides the opportunity to discuss solutions to make change.

U3: “I think the group one just because there's a lot more like meaningful concepts on there. Uh I mentioned before, like, one half of my entire flowchart was just listing types of transportation and realistically that, like, there's not much to go from there, you just stating a fact. But we mentioned like, things to take into account with the group one. Like, again, like purchasing locally, which is an important thing to do.”

G4: “I think I liked the two group together maps, because I think it did kind of bring them together more. And so I think, to that level, it made it, I hate to say it, but it made it like more interesting to me, I guess just being able to see like, it's not just like these two things mix, and you get this product, it's like these two things mix, and you get this product and it matters because of this.”

G2: “If I were to find one, I could talk about would be the fact that if we want to find a solution to climate change through chemistry, we really have to sit down and discuss it with other people like it won't happen on its own. So having opportunities like this, to sit down and think about climate change, and chemistry solutions, that's what's going to help to make change. Umm, if we don't find these opportunities to discuss, it won't happen.”

From group task (Task 3):

G2: I guess that we see completely different aspects but there are still correlated, like there are still linked. There not so exactly, as you said, there 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, there is still the other side is 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 compromising between

	all these aspects. G1: I also think it's like little change in each aspect will help. You know like. You do have to put all your eggs in one basket. Maybe changes here and there from throughout your life. Hmm, that would help a lot because if you like... Let's say if you say, I am going to be vegan which is you know great. But you ride, you drive everywhere, or you buy things from like cheap store, like you do fast fashion... You are still. You might be helping in one sense but there are still other things you can do. So, I think it's like taking in conscience, et just like putting grain and salt in each thing and changing different aspect of your life and not just one." From group task (Task 3): U17: How would we get people to change it though? U18: I know...I think, like the big thing, like we were just talking about is ...when you look at the resources telling you to like live a greener life, people are really pointing to...the most obvious you think of are like, greener cars, you know, like, see all these like electric car outlets at like malls now and stuff. So, I think it I think it's like re-informing people, you know, like, maybe choose the solar panels. U17: Clearing up some misconceptions that we had, because honestly with the way they show things we would think that transportation holds a bigger part in everything else, but kind of doesn't. U18: Yeah, I think ... it would definitely be about... clearing out the misinformation and trying to like, re-educate people on what is actually happening... because ... it's...painfully clear when you see it all together and how everything effects on that diagram."
Collaboration helps the development of ST skills: Collaboration helps participants identify additional concepts and connections (i.e., would add more concepts to individual system based on group task, finds connections between different ideas more easily in group setting) Collaboration helps participants identify	Concepts and connections: Interviewer: "Is there anything you would add, remove, or change to your individual visual representation after participating in the group task?" U9: "I would add more on the plastic I would make the material bigger umm and not include only um the problem, maybe have developed it somehow to include possible solutions and what are the causes that are causing these things to happen." 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

emergence (i.e., group task helps identify a greater purpose of the system map, participant recognizes group members perspective made the topic bigger picture)

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."

From group task (Task 3):

G6: "I feel like there were kind of some more obvious connections that we made at the beginning like that with. Like you were transport uses this, and we require transport with agriculture kind of thing. But I feel like ... that's kind of where the connections would have ended if we were just putting them side by side. You know, like I feel like we were able to find more connections and kind of see more of a connection between the two topics when we had to smoosh 2 maps together as opposed to just keeping them separate and say they're probably related."

Emergence:

U3: "But yeah,...[the system map] kind of like shifted to transportation of like organic...food in general, like the transport of food from one place to another, and we kind of talked about, like, eating locally, or like purchasing locally...They that's how the actual flowchart shifted."

G4: "I think because I was thinking about just the one topic, it was kind of a narrower focus, I guess. And so, it was just saying, like, I know that it's probably not great if we're spraying chemicals into the air kind of thing. And then when he added his part in, it also became about like, while it's not just only on a farm level, it's also getting it from farm to **you** kind of thing...So it kind of made it into a bit of a bigger thing. I guess if that makes sense. Like it kind of made it more um a big, big picture kind of thing, as opposed to just looking at one aspect."

From group task (Task 3):

G1: "I really like your emphasis on biodegradable stuff, hmm, and having. Huh. Like using enzymes to degrade different types of compounds. Huh. We can tie it into like furthering our composting habit for farming and agriculture."

G2: Uhm. Yes. So, we could use, hmm, biological organism to, hmm, re, hm, remediate waste from farms. I think there is actually in Ottawa... The agricultural farm is doing things like that. They use biological organisms to, hmm, to modify farm waste into useful, hmm, things like for. Huh. I know how to

		say it in English but in French it's "de l'engrais". So, it's for the land."
Challenging experiences constructing system maps collaboratively	Difficulties with making connections: Different ideas and topics make it hard to make some connections in the group setting.	G1: "It was definitely harder I found because like, not only you have your own ideas, but you also have to...include other people's ideas. And I found that like, in our case, we had very different...topics like I found that...agricultural land use kind of ties very well into transportation and transportation ties very well to energy and things like that. But like we had kind of like very far ideas that don't tie into each other as...easily. And so, it was kind of hard to find some connections I found."
	Overwhelming experience: Looking at more perspectives and concepts make it a bit overwhelming	U12: "at first for us...it took a while to connect all our ideas together ...just because we kind of attacked our topics at different angles." G4: "I was just saying...I know that it's probably not great if we're spraying chemicals into the air kind of thing. And then when [group member] added his part in, it also became about like, while it's not just only on a farm level, it's also getting it from farm to you kind of thing. So, it was almost a bit more like overwhelming. Because ...it's not just like don't use fertilizers, it's like, you also need to figure out ...more environmentally friendly ways of transporting kind of things."

Theme 2: Participants made chemistry concepts and connections despite having difficulties		
Category	Codes and description	Exemplar quotes
Varied approaches to adding concepts	Include general concepts from personal experiences: Concepts were added based on thinking about what they know about the topic, knowledge obtained from experiences related to their daily and personal lives or knowledge obtained from discussions with others.	U3: "Um, it just seemed like something I could, like, give insight about, I guess, a lot of them are pretty broad. But transportation is something like, I, I use transportation often. So, I thought I could talk about that more." "It was kind of just like a brainstorm um. I just thought of it because I just read objects, phenomena processes." U14: "I just watched the dune Attenborough documentary, and that's how I know most of that" U18: "But so I just thought of like the three main things, I guess that you first think of transportation, like especially being a student, it's like, access, availability, convenience" 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 emission, greenhouses gas emissions. A lot of people have a hard time doing that because of either dietary

restriction. And honestly just like culture. Hmm. Coming from a Latino family, it is incredibly hard to 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.”

G6: “The reason why I chose that [topic] was because that's something I'm working in as a student and as a biochemistry student, my project involves bringing an interface and chemistry.”

Include concepts using a systems thinking lens:
Concepts were added by thinking about, solutions to a problem, causes of climate change or causes that impact the environment, concepts that have many connections, inputs and outputs, and/or zooming in and out of perspectives.

U9: “Like back to the natural fuels, the things that came out at the top of my head when I thought about, like, the idea of um, global warming or climate change, and then relating it back to the to the concept, like what is happening that is causing that.”

Include disciplinary concepts by thinking of chemistry's relevance to topic:
Concepts were added by thinking of how chemistry relates to the topic or from a biology perspective.

From interview:
U10: “So that’s when I introduced the chemical process, combustion being the breaking of bonds, that therefore an exothermic process, and now the energy that is released from that exothermic process is what powers the vehicles; however, that that there are some byproducts from that combustion process that are gaseous in nature, and the gaseous, the gaseous byproducts. Gaseous byproducts are released into the atmosphere combining with air to form molecules that can degrade the ozone layer or capture heat.”

G2: “A lot of materials we use now are based on polymers. So, if we were trying to solve this with chemistry, finding polymers that aren't hard to degrade could be something to consider, especially polymers that already exist in biological organisms, because that means there's already reactions that exist in nature to degrade those, we wouldn't have to come up with complex chemical reactions to be able to degrade them.”

From group task (Task 3):

U6: “So I'll first start off with bikes, there's obviously less damage to the environment because there's less co2 and methane production. And then there's public transport and carpooling, which can decrease the emission of co2, 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.” G2: “I was thinking about how we can use bio-organisms to degrade some materials that we no longer need. Or that would pollute the planet. And also using bio-organisms. So, imitating biological processes where polymers are formed. So, we could use biomolecular polymer to make materials that are easier to degrade afterwards when we no longer use them.”
Awareness of chemistry presence in tasks	Realize system maps lack chemistry concepts and connections: Participants realize their system map does not include many molecular level connections, it is not heavily chemistry related, they could focus more on chemistry aspects, or they would include more chemistry concepts and connections to their system map. Engaging in activities reminded participants of chemistry’s presence: Participants indicate the group task reminded them about the chemistry behind concepts and their topic or that engagement in the study made the participant think about how chemistry is always happening in our life.	G2: I certainly realized that my representation isn't necessarily super chemistry related. It was more conceptual, I don't know. Um, I didn't include many chemistry concepts. Like I didn't talk about orbitals or specific reactions. But at least it does show that chemistry is also related to real life.” U3: “Because in the actual question, it says, try to touch on the molecular level. And if you look at my flowchart that doesn't really touch on that too often. So, I tried to, like, have at least one point relating to it.” U12: “I would say doing this, I realized that I definitely could focus more on the chemistry aspects of climate change, because um usually, I would hear about it and from like reading news stories, or conversations with people in general, so we don't really get too, too into the, the finer scientific details of climate change.” U9: “I just thought just like looking at or working with this project. I thought chemistry is basically our life... because anything that we're doing even like writing any word with a pen or pencil, ... basically chemistry is happening, or at least at some way, at some point in this reaction. In the manufacturing of this piece of paper, or this pencil or this pen, there has been chemistry involved. So, like we can't deny the concept of chemistry, no matter what way we look at things. G4: “I think his [system map]...was a bit more like kind of reaction, molecular based kind of thing. ...so, I think, overall, it just helped me to kind of bridge my interest in what I thought was cool. And what I was thinking about with the chemistry that was... not necessarily behind what I was saying, but the chemistry that was related to it. “ “... hearing another person talk about [the system map], it kind of reminded me of aspects that like, I

		know the chemistry behind [the topic], but I don't necessarily think about it all that much kind of thing."
Difficulty with incorporating chemistry concepts and connections	Describe surface level chemistry concepts in connections: In interviews, participants demonstrate difficulty through their responses to explaining how a macroscopic concept connects to a molecular concept. Participants use macroscopic level contexts and concepts (e.g., environmental context, culture, politics, government) to explain a connection between a macroscopic and molecular level concept made in their system map. May touch on molecular concepts in their explanation but do not go into depth of molecular processes involved when explaining connection. During group task, when participants share their system map with group members, some participants may touch on molecular level concepts but describe chemistry connections using descriptive features or do not get at the depth of chemistry concepts.	U5: "I did land use in agriculture...I started with photosynthesis for like a chemical because it's a chemical process. And I wrote like, what it was, and so it's kind of like one of those naturally occurring processes." U6: "Transportation is divided into public transport, and like carpool also. And then the second one would be just separately, so cars and vehicles. And the public transport and carpool can also kind of be sort of similar to not, not really, really kind of to bikes. Because bikes, it doesn't include any, any use of gas emission or fuel. And so, I'll first start off with bikes, there's obviously less damage to the environment because there's less CO₂ and methane production. And then there's public transport and carpooling, which can decrease the emission of CO₂, 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 CO₂, 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." Interviewer: "So I'm going to ask you to connect how carbon dioxide relates with money and the government." G7: "Okay. Um, well, the first one that comes to my head, ... I think it might be there in a way. But the government is run by people. And when we breathe, we release CO₂. So that's the thing that number one way to connect it, but I kinda touch on that before, the government runs programs, and most of them are based on money they're going to generate from it, revenue, or taxes or whatever it is, or money that we'll need for those programs for environmental changes. And I think CO₂ is like the most non, like gas. It might not be the worst, but it's the one everyone talks about, really. So that relates in that way, but also how, like, they own the bus, I don't know if here it's a thing, but in Brazil, at least they run the bus companies in a way or the public transportation. And so, they are in charge of a lot of those CO₂ emissions or making policies of how much you can drive, how many times you can drive in a day, or, you know, like the types of fuels they are allowed to be used and all that. So, it really, I think they have a strong connection with CO₂ and just like any pollutants, in general, because at the end of the

day, if they say that we can use them, we're not going to be able to use them."

Interviewer: I'm going to ask you to explain how they connect. So, I'm going to ask you to explain how sustainable farming connects to this point, right here, natural gas is not the best in terms of CO₂ production.

G1: "Um sure, so as we know, like a lot of having like meat, like cattle, a group of cows is cattle yeah, um cattle, and all that is not good because like you are basically like, there's a lot of methane that gets used, which is natural gas. And then when this is more like um, if you look like I remember, like the little like, I don't want to call it a game, but the little thing that you, Yeah, simulation. Um you can see that like, using natural gas for energy is not the best in terms of CO₂ production, like the amount of CO₂ production that you make. Um and so it's finding, are there ways to use that natural gas back in the farming um industry, or reuse it for other, other um uses, but I still trying to limit the CO₂ production?"

Indicate difficulty creating chemistry concepts and/or connections:

Participants indicate they have difficulties with making chemistry concepts or connections through one or more of the following instances:

-Mentions they are not really sure about or found it difficult to make a connection from a phenomena concept to a chemistry concept.

-Generally states that making connections to chemistry is hard.

-States that it was hard to talk about the topic in chemistry terms or they had an easier time creating

G1: "Um, [the experience] was actually kind of hard because...I'm in more organic chemistry. And so, my experience like, I know this from a normal experience, like colloquial terms and stuff, but I don't have that much chemistry experience with this type of research and stuff like that. So, it was definitely hard to be like, okay, like, let's try to talk about it in chemistry terms.

Interviewer: How does CO₂ right here connect to electricity?

U9: "Okay, hmm so that's a tough one."

G4: "I definitely had an easier time with this coming up and looking at like the large-scale things as opposed to on a molecular level. And I think that mostly just comes from, like what I was saying before, like, my knowledge comes from my dad was doing, what my brother was doing. And...they don't talk about molecules in what they do so...So those thoughts just kind of came from discussions with family members."

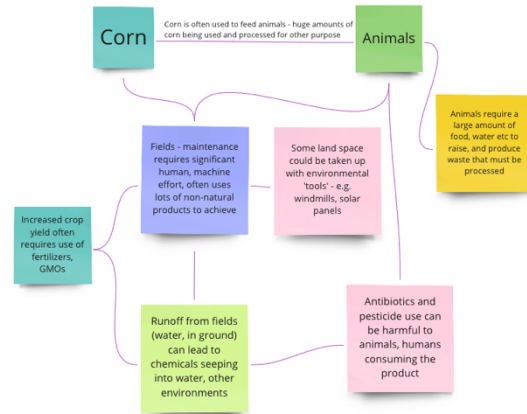
G4: "I had trouble kind of thinking of the molecular level of my stuff outside of like phosphates and stuff exactly like what the fertilizers are made of other than that."

concepts at a larger scale than a molecular scale.

Theme 3: System maps include problems/solutions and causes/effects and differ based on the intended purpose to construct and how they're organized

Categories	Codes and description	Exemplar quotes
Added causes/effects and problems/solutions using different organizational strategies	Participants primarily added ideas to their system maps thinking about causes and effect and/or problems and solutions. The approach used to organize these ideas differs among participants.	Interview question: How did you decide to add onto areas of your visual representation (system map)? G4: “So my thought for putting fields in the middle was that I guess both physical and conceptual, like this is kind of the midpoint, like, this is where things grow. and this is where things come from. So, fields was kind of in the middle, because it's, you need to do things to the fields and fields do things to the area. So that was kind of why I made that my central point. And then umm I kind of separated I guess from there from like, the things you try to do on a farm, so like, grow, produce, raise animals, whatever, on. So those are on the top. And then on the bottom was like the more chemical side of it, like, fertilizers, GMOs, and the effects of those kind of moving forward.”
	Organized by topic, then added subtopics, then ideas: Some participants organize their system maps starting with their main topic, branching into subtopics, and then adding ideas based on these subtopics.	Interview question: How did you organize your visual representation? G4: “I organized it on like, things you do and then the effects, I guess, are like the things you're trying to grow, and then more like chemicals and things you use to get there. umm. So that would be kind of the large structural feature, I guess, of the map. Then I decided to connect those two parts by looking at animals, or comparing or connecting animals to antibiotics and pesticides, umm and how those are harmful to animals in humans, just because umm that, I just kind of felt like that was the biggest connecting thing between the two.”

G4's individual system map:



Organized by topic then added ideas:

Other participants organize their system map starting with their main topic and adding ideas to this topic. Some of these participants who construct their system map via this strategy indicate they lack organization in their individual system map

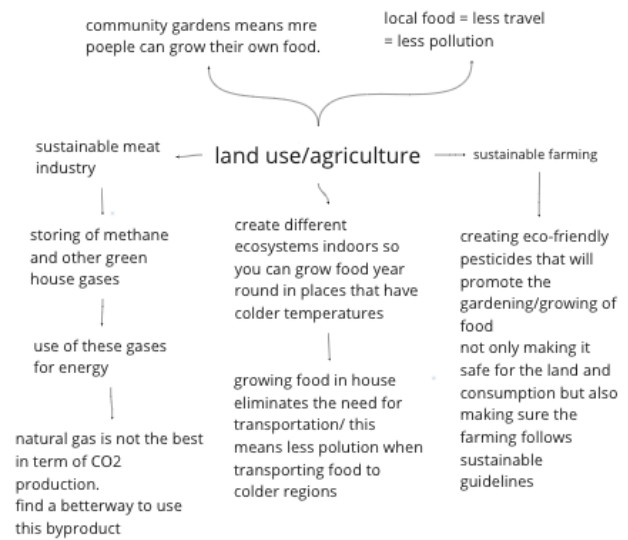
Interview question: How did you decide to add onto areas of your visual representation (system map)?

G1: "I just ... kind of like took the concept of like, how can you...better and make agriculture more sustainable art, let's call it and then just started to ..., when I think of sustainable agriculture, what do we think of it just started ... branching out my idea. So just kind of started growing from that. And then like, as soon as I would have one thought, if I had another thought from that it was like I ... kind of add on."

Interview question: How did you organize your visual representation?

G1: "I kind of just, there's no organization...I kind of just like, wrote the first thing and ... drew an arrow to something that related to it, and then drew an arrow kind of thing. Very chaotic...Kind of like if I was writing on a piece of paper, there was an elementary organization."

G1's individual system map:



Interview question: How did you organize your visual representation?

G7: "I think I didn't organize. If I had more time, I would have organized it better, because I love a good flow chart. But,...I think it's all over the place. I just tried to put things in a place that I could connect to other things. Because I started with...I'm going to go down in like a family tree kind of way. Um, but then...I started to notice that I was actually going to link four things or five things to one box. And I didn't think of that initially that or that would happen, then it kind of just got messy."

Interpretations of the purpose of system map construction influences how they construct it

Intentionally kept concepts broad:

Participants wanted to keep system maps simple by not including many details or expanding too much on other topics/issues.

G2: "I also tried to keep [the system map] simple. So that someone who read it could kind of get where I was going um, yes, so I would say, I tried to not add too many details and keep it simple kind of like how you make a summary when you're studying. Um just the main ideas."

U3: "If there was enough time, obviously, I could probably like one of the topics was electric, like vehicles, I could probably make a whole flowchart about that, but I didn't want to go too specific into things that weren't necessarily about, like transportation directly. I didn't think that's where, like, you guys wanted us to kind of go with this. I thought, like, we're talking about transportation and related with other things as well. So yeah, I just kept it broad."

G1: “I also felt that there was a point where like, points were taking over other issues in the sense of like, for example, local food, less travel, less pollution, that can also tie in with transportation. In terms of like, then you're also dealing with types of transportation and ... how you transport things, and how to make that more sustainable. So, then it starts branching out into other points. Same thing with like, you know, storing and using the gas for energy that goes into another point. And so as soon as like, I started to ... branch out a little too much. That's when I was like, okay, this spot ends here. Because it's now branching on to another, I guess concept.”

Refine system maps for different audiences:

Some participants mention they would construct their system map differently for educational purposes or something other people would view instead of having a system map that is like a brainstorm or something they naturally categorize ideas.

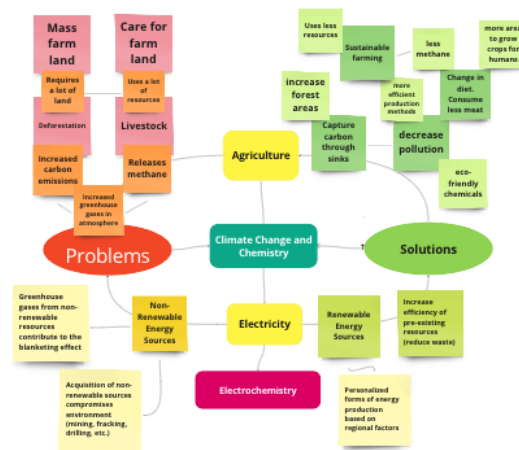
P12: “It's more brainstorm type of visualization instead of like, something that I would show to people to educate them?...So this would just be how I naturally would categorize all the ideas and haven't thought too much about how I would make it more presentable for educational purposes. But besides making things prettier, but that's pretty much it, it's just the fact that this is more instinctual, an instinctual organization rather than more of a designed organization.”

U3: “I mentioned, like listing the types of transportation it wasn't that important, but at the time, the way I was thinking about it, I feel like that's what led to the final decision. So...I don't think there's any reason to take it out, especially since it's just a flowchart. Like, if it was something I was, like, handing in or something that other people have to view. I'd like to refine it, but it's just like a brainstorm. That's what it is.”

Most groups construct a new system map starting with a new topic then adding problems/solutions and causes/effects

Start with new topic then added ideas: Most groups constructed their system map from scratch starting with a new topic (different from their individual topics) that emerged from their conversations. The rest of their group system map focused on adding causes and effects and/or problems and solutions related to this new topic.

U11, U12, and U14's group system maps:



U11: “Okay. So, I guess in the middle, we would have something like climate change in chemistry, or with that would, somebody prefer something else?”

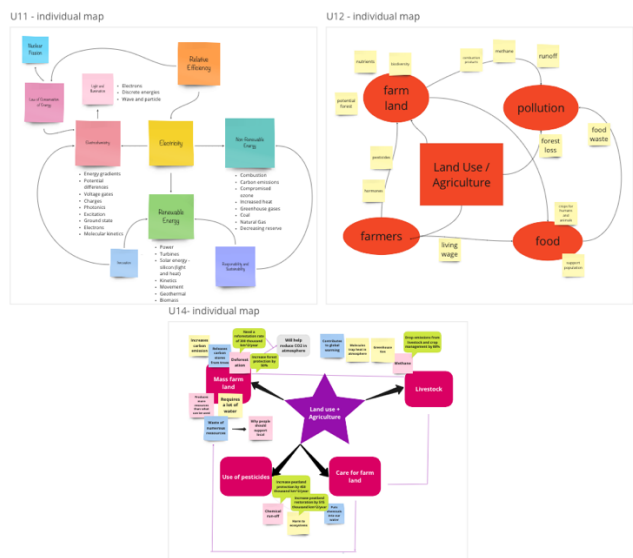
U12: “Yes, something like that.”

U12: “Maybe we can have electricity and agriculture on opposite sides and then like on one axis, and then on another axis would be how they contribute to climate change. And then what are ways we can reduce their contribution to climate change.” U11: “All right. Yeah, I like the opposite idea that make things organized.”

U12: “Maybe we can call it problems and then solutions on the horizontal axis here.”

U11: “So problem, problems and solutions would be on the horizontal and then on the vertical we'd have electricity and land use.”

U11, U12, and U14's individual maps:

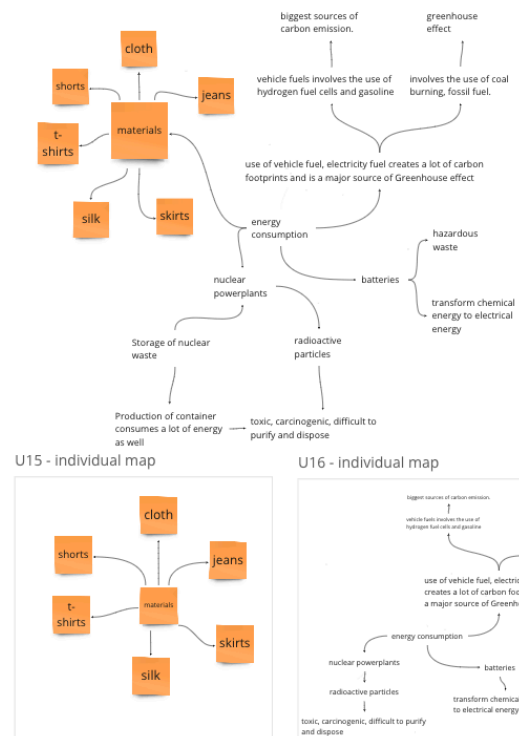


Place system maps side by side and tried making connections: Other groups copied one or both participants system maps, placed them side by side and tried to make connections between the concepts.

U15: “Okay. So, I was thinking like both of us have the carbon emission.”

U16: “Right. Maybe we can like, because my central like idea is energy consumption and you can create a branch that says materials and then you can put like clothes, jeans, shorts, stuff, so I'm just going to move it to the middle or to copy yours to the board.”

U15 and U16's group and individual system maps:



Theme 4: Limitations to system map construction included: Time, knowledge, and technology skills

Category	Codes and description	Exemplar quotes
Time	Creating a system map takes time: Participants run out of time to add to their individual system map before and after engaging with the simulation. Time is also a factor when creating the group system map. Participants mention they would add or make changes to their system maps if they had more time.	Interviewer: “How did you decide to stop working on areas of your visual representation?” U9: “I think if I had more time, I would have developed it and added more things into it, because I don't think it's complete. There are many other things and the things that I included in my visual presentation, that should be included there. But I just didn't have the time to elaborate on it.” U5: “And then it's like, I also included GMOs, but I didn't have time to add to it.” U12: “I also did agriculture and land waste but obviously yours is a lot, a lot more detailed. me like over an hour to really make a good visualization.” U14: “I think I would have liked to connect, like electricity and agriculture together more. But I think time constraints that would have taken a lot more time.

Knowledge	Knowledge limitations prevent expansion of system maps: Participants stopped constructing their system maps due to not being able to think of anything else to add. G4: “I guess part of it was I ran out of time.” G2: “So I think our group visualization, we didn't have the time to really make it visual, we didn't put boxes.” G7: “... if I had more time, I would give it much more thought and came out with more connections and words.” U3: “I did transportation too, it's pretty similar. The ones I have questions on them, just because like, obviously, I didn't want to do any, like research or just things I don't know necessarily.” U8: “Okay, so I choose agriculture as the topic. And I don't know a lot about it. But I put there what I know.” Interviewer: “How did you decide to stop working on areas of your visual representation?” U3: “It was mostly one, like, I couldn't really think of anything else to add to [the system map].” G4: “The other part, I think, I would just say... I kind of ran out of, I guess, knowledge, ...like I said, most of this came just from conversations with people. So, it's like, I don't actually know that much about farming about watersheds and stuff like that. So...I just kind of wrote what I knew and connected it as best I could, but then I kind of didn't have much else to say.” G7: “I think it was just a matter of a quick response word, not coming to my head. So, I could have gone further but then I'll have to, it wouldn't be as quick, I'll have to actually stop and think further about it. And then I will run out of time.”
Technology skills	Problems with tools used during system map construction: Participants stopped constructing their system map because they had problems using the online interactive whiteboard tool (Miro). U9: “So mine is a mess. I just didn't know how to use [Miro]” G1: “I had a hard time with Miro. I am just like; I don't know how this works. Hmm, let me. I am trying like...” Interviewer: “How did you decide to stop working on areas of your visual representation?”

G1: “Mostly when I was like, I don't have space in my square anymore. And Miro and I don't get along in the sense of like...I couldn't make things smaller.”

8.3.2.2 S2.2 Additional theme from students' experiences (not shared in the manuscript)

Simulation helped shift participants' perceptions about making connections in their system maps

Helped participants think differently about making connections: Simulation helped shift participants' way of thinking about tackling a problem to something more purposeful or helped see potential solutions for and connections to climate change.

U18: “Yeah, like if that. Like, simulation is like 100% accurate. That's some serious misinformation that people have. Because like I, you know, I try to stay like informed, but I did not realize it was that big of a like that big of a difference.”

U17: “Of course, it was shocking, to say the least.”

U18: “...Like, yeah, clearing out the misinformation and trying to like, re-educate people on what is actually happening, like, with all of them, because I think it's like, really, like, painfully clear when you see it all together and how everything effects on that diagram.”

U3: “I think that after looking at that [simulation], I kind of shifted towards a more like, environmentally friendly, thought process of it, kind of like what I was mentioning before, because before I was like, oh, this fuel is electric. There's diesel... But after looking at [the simulation], I kind of tried to add a little bit more on how we can change it.”

G2: “So the reason why I added that was that it's only after looking at the [simulation] that I realized I was more focusing on pollution, rather than climate change. So, I added that the solutions I was proposing were mostly to reduce waste that we let go into the environment. Whereas the main focus here was actually climate change. And this is what I added on to the representation that, although solutions I was proposing don't directly relate to pollution into the atmosphere that changes climate, it does uh contribute somehow, through the processes we use to produce materials. It does release pollution into the environment that can contribute to climate change. And it also contributes to um exacerbating the damages pollution does in the environment, and um biodiversity and ecosystems.”

U1: “It's just like mine is just focused on the problem, and what are the causes of the problem, but this simulation is more focused on the problem and a solution and what can be an extra problem.”

Helped make more connections: Simulation helped participants identify connections between concepts.

G7: “Okay, so the question is, how did I decide to make changes or add to my visual representation of visual information? Because I think, the from the simulation, I think the thing that jumped out most was the money and government aspect of it.”

U12: “The biggest thing I got out of it is how the association between farmland and forest land.”

G5: “And I guess what else do I have to say, yeah, with the, with the 2nd intervention or the second exercise, I basically just learned that there was a lot more components that I had originally thought of and like things like the forest, I didn't think of forests at all. And like CO2 emission like that has to somehow be quantified.”

Helped recognize the feasibility of connections: Simulation helped participants recognize the feasibility of connections based on what is realistic or what is easy or not easy to change.

G7: “I think [the simulation] changed more my perception of the visualization, I did, then actually changing the connections themselves, they just added a little bit more of, you know, like reality, instead of being you know all those you are easily connected, and I can easily change them. But it's not like, the reality is not that simple.”

U12: “The biggest thing I got out of it is how the association between farmland and forest land. So ...the basic idea is forests and beach land, or other natural, more natural habitats are carbon sinks that take carbon away from the from the atmosphere... However, it's not completely feasible to just ...keep turning farmland back into more natural forest land, because, like I mentioned, we do have a growing human population. And um so it's not, it's not an easy problem to tackle.”

G1: “Once I saw the simulation, I saw that like, okay, using natural gas for energy is not exactly the best option, either. And so...that's how I decided to change different things of like,... reusing the natural gas for energy will still affect the environment quite a bit. ...If that's still going to happen, like how can I still better something and that's why I try to

focus on basically transportation of goods, almost kind of like almost switching the concept I was working on.”

8.3.2.3 S2.3 Student perspectives codebook

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

Theme 1: Participants believed that systems thinking is beneficial for learning.

Definition: Systems thinking (ST) may help students gain a better understanding of chemistry and its application to the real world, including connecting ideas and phenomena. ST gives a greater purpose to learning and allows students to engage in critical thinking.

Category	Codes and description	Exemplar quotes
Helps students with connections	ST helps students understand how and why ideas are connected. Participants mentioned they think ST can help other students understand how and why ideas are connected and how concepts can influence other connects. Additionally, participants believed students would have a better understanding of the topics and how they connect to chemistry	ST question: How might a systems thinking activity affect students’ perspectives towards chemistry? Responses: G7: “Observing how things are connected both within a similar group (types of fuel) and between very distinct things (combustion, release of energy, breathing) may help students to connect concepts in chemistry, specially between disciplines (organic, inorganic, biochem, material science, etc.).” U9: “Well first of all, they won’t hate it anymore, but more broadly they would be able to comprehend the reason behind why things happen the way that they do, under what circumstances and what would happen if we were to remove them.” G2: “They can see the big picture and understand the role of each element in the system, i.e. how concepts in chemistry can culminate into something useful for society.”

	Physically making connections between concepts is helpful. From the interview, one participant mentioned their experience with the ST tasks was good because physically making the connections between the concepts was very helpful to them.	Interview question: How was your overall experience when creating visual representations from a chemistry context? Response: U12: “Umm it was really good because some, in a sense, we, like, I know that all these concepts are connected but having to actually physically make the connections between the concepts was, was very helpful. And um again, focusing on the chemistry side of things I, it made, it made it more apparent how chemistry is um very essential in almost every step in almost every connection, whether between farmers putting chemicals into the farmland, or what chemicals are produced in the farming process, and maybe chemicals even in, in the food that we eat umm. So yeah, definitely very helpful. Putting ideas into uh into a visual representation.” Interviewer: “Can you elaborate what you mean by helpful?” U12: “helpful in terms of making connections clear and um basically making things clear, and um really highlighting um where chemistry shows up and all of these processes.”
Helps students with learning chemistry	ST helps students better understand chemistry and its applications to the real world. Participants believed ST can help students relate real life concepts to concepts shown in chemistry including chemistry’s applications to the real world. Additionally, participants believed ST could help students make stronger connections and gain a better understanding of the chemistry content.	ST question: How might a systems thinking activity affect students’ perspectives towards chemistry? Responses: U14: “Systems thinking activity could help a student make stronger connections and deeper understandings in chemistry.” U8: “A well-known knowledge of systems is essential for students to know how to deal with chemical sciences in the macroscopic and microscopic terms and to evaluate it as a whole.” U2: “A systems thinking activity may affect a students’ perspective towards chemistry because it helps them relate concepts that they are able to apply in real life to concepts showed in chemistry. This helps those students who find chemistry challenging gain a better understanding of the material being taught to them.”
	ST gives students a sense of purpose or importance when learning chemistry: Participants believed ST can make chemistry learning have a greater purpose and	ST question: How might a systems thinking activity affect students’ perspectives towards chemistry?

	show the importance of chemistry as it relates to problems in their lives.	Responses: U12: “It would show the importance of chemistry as it relates to problems that affect our lives.” U3: “It may make learning have a greater purpose to it. Often people are discouraged to learn about things that they "won't" need in the future and so knowing the importance of learning these things to an ongoing crisis is definitely an encouragement.”
Allows students to engage in critical thinking	ST promotes critical thinking. One participant stated systems thinking promotes critical thinking and believed brainstorming can encourage students to think outside the box	ST question: How might a systems thinking activity affect students’ perspectives towards chemistry? Response: U16: “It promotes the critical thinking ability of the students. The brainstorming phase helps student to explore in in-depth thinking and encourage them to think outside the box.”

Theme 2: Participants believed that systems thinking helps students gain interest and engagement.

Definition: Systems thinking (ST) may be more engaging for students. Additionally, learning chemistry through ST activities is more interesting for participants and may be more interesting for other students as well. Participants who engaged in the interviews mentioned they had an overall enjoyable experience.

Category	Codes and description	Exemplar quotes
Helps student engagement	ST may help engage students. Participants believed that ST may make chemistry more interactive and engaging for students.	ST question: How might a systems thinking activity affect students’ perspectives towards chemistry? Responses: U5: “It can make it more interactive and engaging for students which would help them find it more exciting.” G5: “Positively, it may help engage students”
Helps students’ gain and identify interests	ST helps students gain interest in chemistry. Participants stated that students will find chemistry more interesting or will not hate chemistry after engaging in ST activities.	ST question: How might a systems thinking activity affect students’ perspectives towards chemistry? Responses: U9: “Well first of all, they won’t hate it anymore...” G4: “I think they might find it more interesting - especially students who aren't super interested in chemistry, but have to take it as an elective, to see how it can fit into what they're doing.”

	ST can help students identify their interests. Participants stated ST provides students the chance to capture their interests such as identifying a field of study/career they are interested in.	ST question: How might a systems thinking activity affect students' perspectives towards chemistry? Responses: U10: "It may provide a student with the thinking necessary to narrow down on a field they are interested in, by providing them with the knowledge of options of how many applications chemistry has in the real world." G8: "Not every student is passionate about the same things. By offering different systems in which they could participate in solvent a conflict, you have more chance of capturing their interest because they can grasp on the one system they feel more passionate about."
Interest/enjoyment from engaging with ST activities	Participants had an overall enjoyable experience with ST activities. In interviews, participants mentioned their experience was good or fun or that they liked the entire ST intervention.	Interview question: How was your overall experience when creating visual representations from a chemistry context? Responses: U3: "But yeah, um, my overall experience, it was good." G2: "I think it was a good experience." G4: "I liked it. I thought I thought it was fun to do and to just kind of a mess around with like thinking about things in a different way." G7: "It was very fun. Actually, it was, I think was better than just listing items. I was able to dig deeper and it kind of gave me a new perception of how my brain works."
	Interest captured from ST activities. From a response to an interview question, one participant mentioned it was nice and interesting to hear about more specific reactions in chemistry from their group member. Another participant mentioned they found it interesting identifying how they view their own connections.	Interview question: How was your overall experience when creating visual representations from a chemistry context? Responses: G4: "I think it definitely was nice to hear about, like kind of more specific reactions and aspects, I guess that he was thinking of in context, in a larger scale context that kind of made it a bit um, I feel bad saying more interesting, I still think it's interesting, but like, I find it easier to like engage with it when it's in a context kind of thing." G7: "I guess I changed how I view my own connections. And that was very interesting. I learned a lot from it. about myself, I guess."

Theme 3: Participants believed ST allows perspectives to be shared and gained.

Definition: Systems thinking allows students to share perspectives and ideas with other and gain new perspectives about themselves.

Categories	Codes and description	Exemplar quotes
Allows perspectives to be shared and gained	ST offers opportunities to share new ideas, perspectives, and insights: Some participants believed that ST provides students the opportunity to look at different perspectives, ideas, insights, and all factors involved.	ST question: How might a systems thinking activity affect students' perspectives towards chemistry? Responses: U11: "Systems thinking encourages a safe space to offer different perspectives and insights, a rather important aspect of learning. Collaborative activities endow one with the opportunity to hear and be heard, thus clarifying ideas through articulation." U18: "it can influence student's perspective by offering a holistic approach by looking at all factors involved - also can influence bias/ or open up new ideas to people depending on the information/ perspective presented."
Participants' gain new perspectives	ST activities gave a participant a new perspective about how they think. In an interview, one participant shared that they liked their experience with the ST tasks because it gave them a personal gain by understanding how their brain works and how they view connections.	Interview question: How was your overall experience when creating visual representations from a chemistry context? Response: G7: "It was very fun. Actually, it was, I think was better than just listing items. I was able to dig deeper and it kind of gave me a new perception of how my brain works. Like, it looks like a picture of part of my brain, like how everything is out of place, but it's still like, closely related in a weird manner. That was very good. Like, I would love to do that. Again, it was very fun...And I know I'm helping you with your study, but it actually just gave me a little personal gain. I guess I changed how I view my own connections."

Theme 4: Participants believed systems thinking provides personal, social, and professional relevance.

Definition: Systems thinking allows participants to view possible professions (personal relevance), clarifies chemistry's purpose in human and social issues (social relevance), and makes connections to their personal lives (personal relevance).

Category	Codes and description	Exemplar quotes
Provides personal relevance	ST makes participants thinking about chemistry's importance and role of climate change to their lives. One participant believes that ST would show the importance of chemistry	ST question: How might a systems thinking activity affect students' perspectives towards chemistry? Response: U12: "It would show the importance of

relating to their life. Other participants who participated in the interview shared perspectives of chemistry's importance and their role in fighting climate change.

chemistry as it relates to problems that affect our lives."

Interview question: How was your overall experience when creating visual representations from a chemistry context?

Responses:

U9: "I think it was just an eye opening. You know, like, I already knew the fact that they're there. I knew them, I believed in them, but like, I never actually brought them to my conscious mind to actually look at them and say, like, chemistry is there, this is actually like, it's not something you just believe in... But actually, doing this um, this visualization intervention, or this research project, like it was actually an eye opening and it just like kind of like, it was a snap this is actually happening and like, you need to give it further thought. Because if not now, when?"

G1: "And I think it also goes back to you know, like, talking about climate change and all that and chemistry where we do make a lot of waste here. And... we don't use the cleanest solvents, so it kind of just got me thinking, what me as a human can do to help fight climate change, like as a human, but there's also like, I have to kind of look elsewhere. Like, how can I do this as a chemist and like, as an organic chemist? How can like fit the little things I do in the lab to help? So that kind of got me thinking like, what else can I do other than just like as a human, but also as a chemist?"

ST question: How might a systems thinking activity affect students' perspectives towards chemistry?

Responses:

G1: "to take a moment to see how your research might affect the world and maybe take some actions to make your chemistry a bit more sustainable."

U17: "A young mind holds the potential to understand current underlying issues about the climate change so making them understand the different types of things that are greatly impacting the change can be beneficial as they can work towards solving and resolving the issue. System thinking's core is that of chemistry so when someone

Provides social relevance

ST helps students identify the need to take action or create solutions to issues.

Participants believed that ST could help students identify things that are impacting climate change so that take action to make chemistry more sustainable or work towards solving the issue.

		wishes to understand things through system thinking they think it through the aspect of chemistry and various aspects surrounding chemistry.”
Provides professional relevance	ST helps students consider future career opportunities or interests: Participants believed ST activities will help students identify alternative career paths and identify fields they may be interested in.	ST question: How might a systems thinking activity affect students’ perspectives towards chemistry? Responses: U10: “It may provide a student with the thinking necessary to narrow down on a field they are interested in, by providing them with the knowledge of options of how many applications chemistry has in the real world.” U4: “This may help a students’ perspective by linking chemistry to real life niches and careers, letting them know that taking chemistry doesn't necessarily have to lead to either researcher or engineer.”

8.3.3 S3. Additional Results, Discussion, and Implications

8.3.3.1 S3.1 Participants made chemistry concepts and connections despite having difficulties.

Additional finding: One participant mentioned that they found it easier to create concepts at a larger scale than a molecular scale based on their prior knowledge (Figure 1).



G4: “I definitely had an easier time with this coming up and looking at the large-scale things as opposed to on a molecular level. And I think that mostly just comes from, like what I was saying before, my knowledge comes from what my dad was doing, what my brother was doing. And they don't talk about molecules in what they do. So those thoughts just kind of came from discussions with family members.”

Figure 1. G4 quote.

Additional discussion and implication: In the context of climate change, prior research has found that students across all levels struggle to grasp climate science concepts due to the inherent complexity of the climate system and the multidisciplinary content knowledge required to understand and articulate key concepts in climate science.^{14–16} In terms of chemistry concepts related to climate change, one study found that undergraduate students have difficulties understanding the particulate-level of greenhouse gases, making it challenging to understand the mechanism of the greenhouse effect and connections to the impact of increasing carbon dioxide concentration and climate change.¹⁴ If such connections are the goal, then educators need to explicitly help students make connections between molecular and

particulate level chemistry concepts and climate change, and there have been a number of resources created to help educators achieve this.^{14,17–22}

Figure 1 highlights that participants may not have had the opportunity to learn about the scientific and molecular connections to climate change, considering where participants gained their prior knowledge on the topic. 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 chemistry curricula is still being taught in many chemistry courses emphasizing students' understanding of disciplinary concepts.^{23–25} Often, this curriculum does not allow students to engage in activities and discussions about relevant personal, societal, or environmental problems,^{23,26} and learners are taught disciplinary knowledge and skills independently from how they are integrated into everyday practice.²⁷ This approach often leads 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.^{27–30}

Universities and chemistry organizations recognize changes to chemistry curricula are needed in order to adequately prepare the next generation to face 21st century challenges such as, climate change.^{25,31,32} Chemistry educators have also been advocating that curricula needs 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.^{25,33–35} As students gain proficiency in learning skills (e.g., ST) in one context, they will gain maximum benefit if they can identify, articulate, and transfer these skills to new contexts,^{36–39} an aspect of metacognition.^{40–43} When implementing a ST activity in a chemistry course, in the context of a specific global issue, it is essential that the educator (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.

8.3.3.2 S3.2 System maps emphasized problems/solutions and causes/effects and differed in terms of organization and the intended purpose

Additional findings and discussion related to organization of system maps:

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. One of these participants described this organizational approach in an interview but it was not visually evident in their system map (Figure 2). The remaining participants organized their system maps starting with their main topic and then added ideas related to this topic (no explicit branching into subtopics); most indicating that their system maps lacked organization.

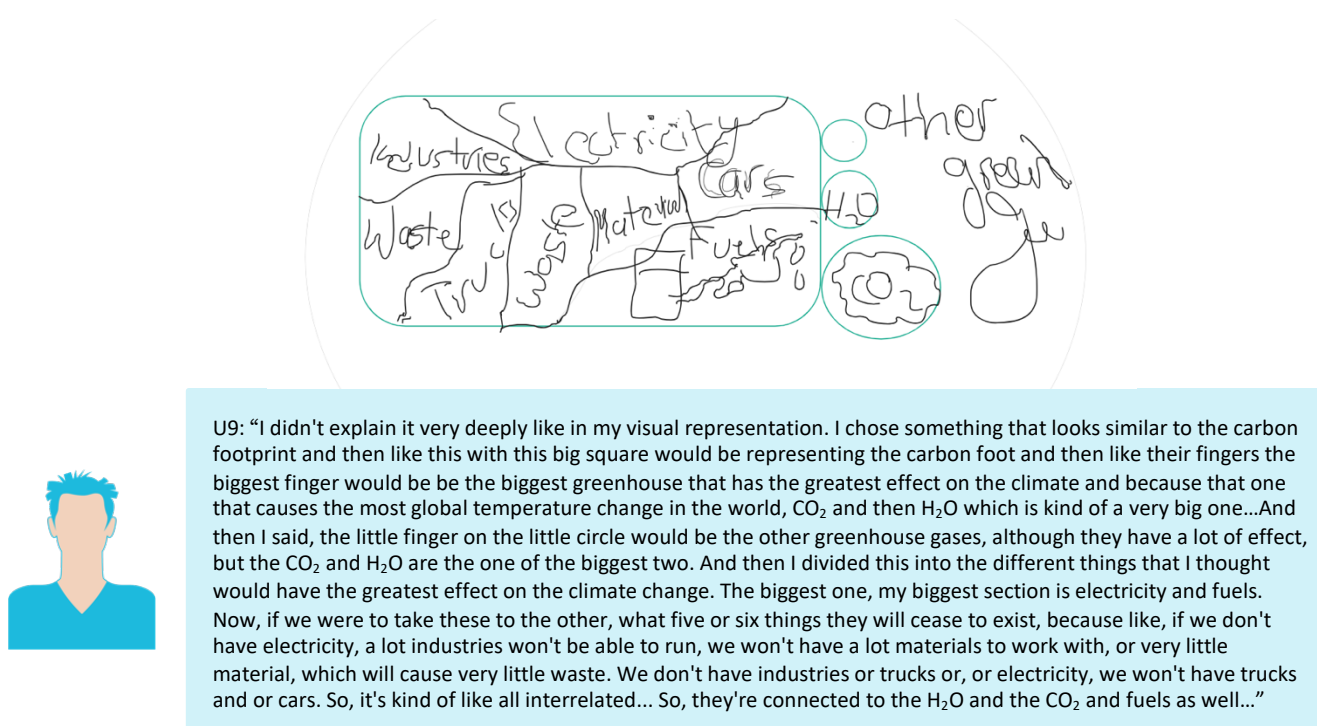


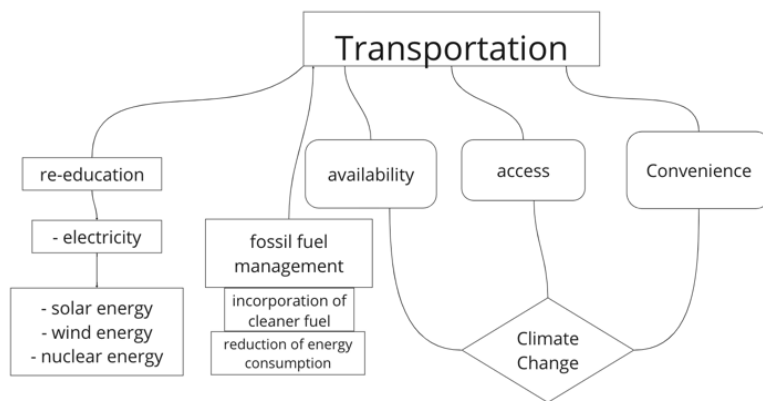
Figure 2. U9 quote and individual system map.

Three of the twenty-six participants used a different approach for constructing their individual map by adding concepts about climate or their topic of interest. These participants constructed system maps starting with an overarching topic (e.g., chemistry, climate change,

transportation). Ideas were added that related to that topic, with no emphasis on causes or effects and merely descriptive connections. It is possible these participants thought of the causes and effects of the concepts they added but were not explicit in adding this to their system map or through their explanations.

Surprisingly, there were a few situations where participants indicated their system map started as disconnected, but during the process, they realized they were starting to make multiple connections to one concept. This suggests that students engaged in metacognitive processes during the ST activity by consciously reflecting on the process of constructing their system map.

We found that using both system maps and verbal explanations gives a better representation of participants' thinking. In most cases, participants explained more connections and concepts verbally compared to concepts and connections shown in their individual and group system maps. In a conversation between U17 and U18, they discussed the causes and effects that they learned from the simulation and how this information was different from their prior knowledge and beliefs, leading to a conversation on misinformation and re-education. However, the new connections they made through their conversation could have been better represented in their group system map (Figure 3).



U18: "I think the big thing we were just talking about is when you look at the resources telling you to live a greener life, people are really pointing to, the most obvious you think of are like, greener cars... So I think it's re-informing people, you know, maybe choose the solar panels."

U17: "Clearing up some misconceptions that we had, because honestly with the way they show things we would think that transportation holds a bigger part in everything else, but kind of doesn't."

P18: "Yeah, I think it would definitely be about ... clearing out the misinformation and trying to re-educate people on what is actually happening because I think it's painfully clear when you see it all together and how everything affects on that diagram (Design Our Climate Simulation)."

P17: "Yeah, people just need to know that energy and electricity holds more impact than transportation."

P17: "Okay. I like your organization better. So maybe we'll incorporate that and just kind of put examples in justification below it?"

P18: "Yeah, should we like rearrange cause we're talking about a lot like new information and informing people. Should we start with that?"

Figure 3. Example of system map constructed by U17 and U18 and their conversation discussing misinformation and re-education.

IPT connection to organization of system map findings: 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 organize their map based on subtopics. 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. Perhaps participants with less organized prior knowledge of climate change could be less able to identify these relevant features to their topic, ultimately finding it more difficult to organize their system map and identify interconnections.

Implications to teaching: In our study, we showed how students approached these ST tasks naturally with minimal prompting so that we could gain a better understanding of their

baseline ST skills and experiences. Our 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).³⁴ When using SOCMEs in a ST activity, educators could first prompt students to construct subsystems related to a global issue they wish to investigate, then prompt students to think about the concepts that make up each subsystem at different levels of granularity (e.g., molecular level). Finally, students can consider how those concepts influence or are influenced by other concepts in different subsystems to create interconnections. Other researchers have mentioned that it may be useful for educators to show students versions of SOCMEs and the process of constructing them to help students understand how to connect their chemistry learning to broader scientific topics.⁴⁴

Additional findings and discussion related to intended purpose:

In some cases, participants' intended purpose of constructing their system map limited the number of concepts or connections 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 (Figure 4).



U3: "One of the topics was electric, like vehicles, I could probably make a whole flowchart about that, but I didn't want to go too specific into things that weren't necessarily about, like transportation directly. I didn't think that's where you guys wanted us to kind of go with this. I thought, like, we're talking about transportation and related with other things as well. So yeah, I just kept it broad."

Figure 4. Undergraduate student 3 (U3) quote.

Complementing these findings, we found that using both system maps and verbal explanations gives a better representation of participants' thinking than constructing system maps alone. In most cases, participants explained more connections and concepts verbally compared to concepts and connections shown in their individual and group system maps. Participants can make more connections than what they included in their system maps; therefore, the purpose of constructing a system map needs to be explicit for the learner and

students' ST skills should not solely be assessed based on the construction of system maps. Previous studies have demonstrated that system maps and SOCMEs can be used to teach chemistry content in secondary and post-secondary settings, but implementation comes with several limitations for both educators and students (e.g., difficult to show and quantify ST skills).^{45, 46–48} Therefore, ST skills require multiple forms of assessment which can include system maps, written and verbal responses as shown in our study.⁴⁵ 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.

8.3.3.3 S3.3 Systems thinking provided personal, social, and professional relevance

Implications for teaching: Our findings show the potential for ST to make connections that are relevant to students personally, socially, and professionally. When students can connect to their personal lives when learning chemistry, they may be more motivated or interested in learning the course content. A study on students' perceptions of socio-scientific instruction using ST tools similarly found relevance as a key theme.⁴⁹ However, they suggested that introducing relevant context alone does not guarantee a productive learning experience.⁴⁹ Therefore, a ST approach needs to include opportunities to leverage students' other long-term individual interests as students' can gain more knowledge and see more value when chemistry content is explicitly connected to these interests.⁴⁹

8.3.4 S4. Systems Thinking Interview Questions

The following questions ask students to reflect on their experiences constructing system maps individually and collaboratively, including their perspectives about engaging with the tasks.

Refer to Task 1

Q1: Is there any significance behind the topic you chose? (Show participants google form responses)

Q2: Please explain how you came up with these ideas/concepts? (Show participants google form responses)

Q3a: How did you decide to add onto areas of your visual representation? (Show participants visual representation on Miro)

Q3b: How did you decide to stop working on areas of your visual representation?

Q3c: How did you organize your visual representation?

Q4: Explain how this concept connects with this concept?

Note: Interviewer focused on distinct, interdependent levels of organization. Choose one concept at one level of organization (submicroscopic) as well as one concept at another level of organization (macroscopic)

Q5: Can you please explain your thought process to your response for Question 5a and 5b? (Show participants google form responses)

Refer to Task 2

Q5: How did you decide to make changes or add on to your visual representation based on the information you gained from the simulation?

Refer to task 3

Q6a: How did your experience differ in the group setting when connecting your visual representations together compared to when you completed the tasks individually?

Q6b: What visual representation do you think is better (individually- or group-created)? Why?

Q7a: What new perspectives did you have about climate change and/or chemistry when collaborating with your group? If any?

Q7b: How did your perspective about climate change and/or chemistry change?

Q7c: Is there anything you would add, remove, or change to your individual visual representation after participating in the group task?

Refer to entire ST intervention

Q8: How was your overall experience when creating visual representations from a chemistry context?

Q9: Is there anything else you would like to discuss/share that we didn't cover in the interview?

The interviewer asked follow-up questions when the interviewer needed further clarification on a response from a student.

8.3.5 S5. Systems Thinking Intervention/Activities

Task 1

Question 1. Choose a topic of your choice that you want to investigate.

- Electricity
- Materials
- Buildings
- Land Use/Agriculture
- Transportation

Question 2. List as many ideas/concepts (e.g., objects, phenomena, processes, behaviors etc.) in one word or phrase that may relate to your topic of choice and/or personal experience.

Question 3. Using the Miro link [insert Miro link] and the features provided in Miro, create a visual representation (e.g., a diagram, concept map, illustration/graphic etc.) of interconnected relationships between the ideas/concepts from Question 2.

(<https://miro.com/login/>)

Question 4. Use your chemistry knowledge to incorporate chemistry concepts into your visual representation. Please include different levels of granularity. For example, focus on things that are visible and touchable as well as focus on the molecular level (molecules themselves)

Question 5a. Imagine that you remove the second idea/concept listed in Question 2. How does removing the second idea/concept impact the rest of your visual representation?

Question 5b. Why does removing the second idea/concept impact the rest of your visual representation?

Task 2

Question 1. Please take 5 minutes to explore the Design Our Climate (DOC) simulation (<https://applets.kcvs.ca/DesignOurClimate/DesignOurClimateSim.html>) on your own and write down any relevant information for your visual representation in the space provided below.

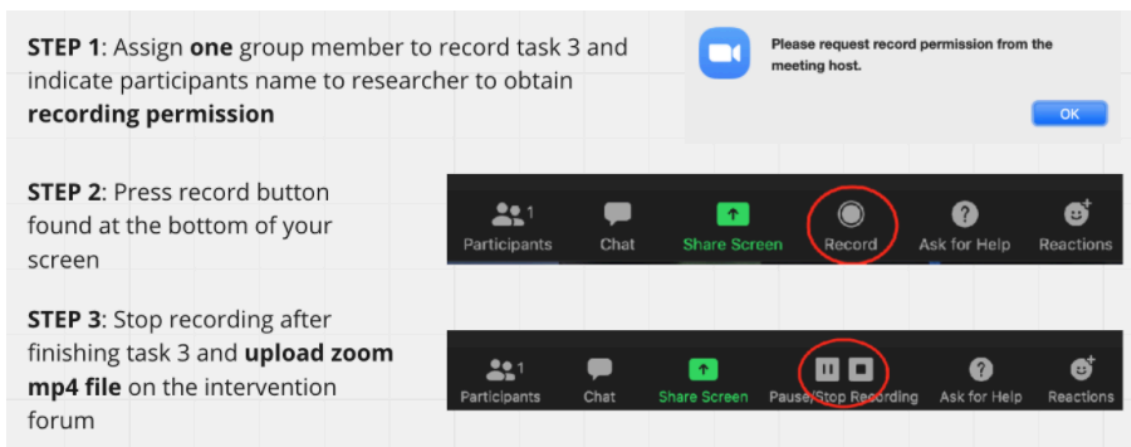
Question 2. Please watch a short 3-minute DOC introduction video on how to navigate through the DOC simulation.

(<https://youtu.be/cXzqmF2JoSQ>)

Question 3. Continue to explore the simulation and write down any relevant information while using the simulation in the space provided below. Additionally, continue to make connections to chemistry. Use this information to expand your visual representation as much as possible. You can refer back to the DOC simulation as needed when expanding your visual representation.

Task 3

Question 1. You will now be placed in a group of 2 or 3 people in Miro. Please assign one person in your group to record your group conversation using the zoom recording feature in your breakout room. At the end of task 3, upload the recording to [link]. Note: If planning to implement this activity in a class, you can skip this zoom breakout room and recording step. Recording was used for data collection purposes in our study.



Question 2. Please share your visual representation with each group member (each group member will explain their visual representation in ~2 minutes)

Question 3. Please answer this question individually. Identify any similarities and differences between each visual representation. Please write your response in the space below.

Question 4. Find a way to connect each visual representation into one larger visual representation on Miro.

Question 5. Please discuss the following question as a group. What is different about the visual representation that you made through discussions than just setting your individual systems side by side?

8.3.6 S6. References

- (1) Xu, X.; Lewis, J. E. Refinement of a Chemistry Attitude Measure for College Students. *J. Chem. Educ.* **2011**, 88 (5), 561–568. <https://doi.org/10.1021/ed900071q>.
- (2) Saldaña, J. Writing Analytic Methods. In *The coding manual for qualitative researchers*; SAGE: Los Angeles, 2013; pp 41–57.
- (3) Birks, M.; Chapman, Y.; Francis, K. Memoing in Qualitative Research: Probing Data and Processes. *J. Res. Nurs.* **2008**, 13 (1), 68–75. <https://doi.org/10.1177/1744987107081254>.
- (4) 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>.
- (5) 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>.
- (6) Schunk, D. H. *Learning Theories: An Educational Perspective*, 6th ed.; Pearson: Boston, 2012.
- (7) 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>.
- (8) 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.
- (9) Bruner, J. Vygotsky's Zone of Proximal Development: The Hidden Agenda. *New Dir. Child Adolesc. Dev.* **1984**, 1984 (23), 93–97. <https://doi.org/10.1002/cd.23219842309>.
- (10) Lincoln, Y. S.; Guba, E. G.; Pilotta, J. J. *Naturalistic Inquiry*; Newbury Park, CA: Sage., 1985.
- (11) Saldaña, J. *The Coding Manual for Qualitative Researchers*, 3rd ed.; SAGE Publications, Inc.: Thousand Oaks, California, 2016.
- (12) 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.
- (13) Deng, J. M.; Streja, N.; Flynn, A. B. Response Process Validity Evidence in Chemistry Education Research. *J. Chem. Educ.* **2021**, 98 (12), 3656–3666. <https://doi.org/10.1021/acs.jchemed.1c00749>.

- (14) Versprille, A. N.; Towns, M. H. General Chemistry Students' Understanding of Climate Change and the Chemistry Related to Climate Change. *J. Chem. Educ.* **2015**, 92 (4), 603–609. <https://doi.org/10.1021/ed500589g>.
- (15) Shepardson, D. P.; Choi, S.; Niyogi, D.; Charusombat, U. Seventh Grade Students' Mental Models of the Greenhouse Effect. *Environ. Educ. Res.* **2011**, 17 (1), 1–17. <https://doi.org/10.1080/13504620903564549>.
- (16) Walz, K. A.; Kerr, S. C. “Holes” in Student Understanding: Addressing Prevalent Misconceptions Regarding Atmospheric Environmental Chemistry. *J. Chem. Educ.* **2007**, 84 (10), 1693. <https://doi.org/10.1021/ed084p1693>.
- (17) Mahaffy, P. G.; Holme, T. A.; Martin-Visscher, L.; Martin, B. E.; Versprille, A.; Kirchhoff, M.; McKenzie, L.; Towns, M. Beyond “Inert” Ideas to Teaching General Chemistry from Rich Contexts: Visualizing the Chemistry of Climate Change (VC3). *J. Chem. Educ.* **2017**, 94 (8), 1027–1035. <https://doi.org/10.1021/acs.jchemed.6b01009>.
- (18) Aubrecht, K. B. Teaching Relevant Climate Change Topics in Undergraduate Chemistry Courses: Motivations, Student Misconceptions, and Resources. *Curr. Opin. Green Sustain. Chem.* **2018**, 13, 44–49. <https://doi.org/10.1016/j.cogsc.2018.03.008>.
- (19) Versprille, A.; Zabih, A.; Holme, T. A.; McKenzie, L.; Mahaffy, P.; Martin, B.; Towns, M. Assessing Student Knowledge of Chemistry and Climate Science Concepts Associated with Climate Change: Resources To Inform Teaching and Learning. *J. Chem. Educ.* **2017**, 94 (4), 407–417. <https://doi.org/10.1021/acs.jchemed.6b00759>.
- (20) Flener-Lovitt, C. Using the Socioscientific Context of Climate Change To Teach Chemical Content and the Nature of Science. *J. Chem. Educ.* **2014**, 91 (10), 1587–1593. <https://doi.org/10.1021/ed4006985>.
- (21) American Chemical Society. *ACS climate science toolkit*. <https://www.acs.org/content/acs/en/climatescience.html> (accessed 2023-11-23).
- (22) Mahaffy, P. G.; Martin, B. E.; Kirchhoff, M.; McKenzie, L.; Holme, T.; Versprille, A.; Towns, M. Infusing Sustainability Science Literacy through Chemistry Education: Climate Science as a Rich Context for Learning Chemistry. *ACS Sustain. Chem. Eng.* **2014**, 2 (11), 2488–2494. <https://doi.org/10.1021/sc500415k>.
- (23) Sjöström, J.; Talanquer, V. Humanizing Chemistry Education: From Simple Contextualization to Multifaceted Problematization. *J. Chem. Educ.* **2014**, 91 (8), 1125–1131. <https://doi.org/10.1021/ed5000718>.
- (24) *Teaching Chemistry – a Studybook: A Practical Guide and Textbook for Student Teachers, Teacher Trainees and Teachers*; Eilks, I., Hofshäin, A., Eds.; Sense Publishers: Rotterdam Boston Taipei, 2013.
- (25) Chemistry Education Needs a Green Reset. *Nature* **2022**, 604 (598). <https://doi.org/10.1038/d41586-022-01109-z>.

- (26) Berkel, B. van. *The Structure of Current School Chemistry: A Quest for Conditions to Escape*; CD-[beta] Press: Utrecht, Netherlands, 2005.
- (27) 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>.
- (28) 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.
- (29) 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.
- (30) Royer, J. M. Theories of the Transfer of Learning. *Educ. Psychol.* **1979**, *14* (1), 53–69.
- (31) Voutchkova-Kostal, A.; Laviska, D. A.; Briddell, C. ACS Launches Green Chemistry Education Campaign.
- (32) Royal Society of Chemistry. *Green shoots: A sustainable chemistry curriculum for a sustainable planet*. <https://www.rsc.org/policy-evidence-campaigns/environmental-sustainability/sustainability-reports-surveys-and-campaigns/a-sustainable-chemistry-curriculum/> (accessed 2023-11-23).
- (33) 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>.
- (34) 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>.
- (35) 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>.
- (36) Perkins, D. N.; Salomon, G. Knowledge to Go: A Motivational and Dispositional View of Transfer. *Educ. Psychol.* **2012**, *47* (3), 248–258. <https://doi.org/10.1080/00461520.2012.693354>.
- (37) Salomon, G.; Perkins, D. N. Rocky Roads to Transfer: Rethinking Mechanisms of a Neglected Phenomenon. *Educ. Psychol.* **1989**, *24* (2), 113–142. https://doi.org/10.1207/s15326985ep2402_1.
- (38) Foerst, N. M.; Klug, J.; Jöstl, G.; Spiel, C.; Schober, B. Knowledge vs. Action: Discrepancies in University Students' Knowledge about and Self-Reported Use of Self-

- Regulated Learning Strategies. *Front. Psychol.* **2017**, *8*, 1288.
<https://doi.org/10.3389/fpsyg.2017.01288>.
- (39) Royer, J. M. Theories of the Transfer of Learning. *Educ. Psychol.* **1979**, *14* (1), 53–69.
<https://doi.org/10.1080/00461527909529207>.
- (40) Dunning, D.; Johnson, K.; Ehrlinger, J.; Kruger, J. Why People Fail to Recognize Their Own Incompetence. *Curr. Dir. Psychol. Sci.* **2003**, *12* (3), 83–87.
<https://doi.org/10.1111/1467-8721.01235>.
- (41) Wagener, B. Metacognitive Monitoring and Academic Performance in College. *Coll. Teach.* **2016**, *64* (2), 47–54. <https://doi.org/10.1080/87567555.2015.1116056>.
- (42) Schuster, C.; Stebner, F.; Leutner, D.; Wirth, J. Transfer of Metacognitive Skills in Self-Regulated Learning: An Experimental Training Study. *Metacognition Learn.* **2020**, *15* (3), 455–477. <https://doi.org/10.1007/s11409-020-09237-5>.
- (43) de Bruin, A. B. H.; Kok, E. M.; Lobbestael, J.; de Grip, A. The Impact of an Online Tool for Monitoring and Regulating Learning at University: Overconfidence, Learning Strategy, and Personality. *Metacognition Learn.* **2017**, *12* (1), 21–43.
<https://doi.org/10.1007/s11409-016-9159-5>.
- (44) Aubrecht, K. B.; Dori, Y. J.; Holme, T. A.; Lavi, R.; Matlin, S. A.; Orgill, M.; Skaza-Acosta, H. Graphical Tools for Conceptualizing Systems Thinking in Chemistry Education. *J. Chem. Educ.* **2019**, *96* (12), 2888–2900. <https://doi.org/10.1021/acs.jchemed.9b00314>.
- (45) 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.*
- (46) 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>.
- (47) Reynders, M.; Pilcher, L. A.; Potgieter, M. Teaching and Assessing Systems Thinking in First-Year Chemistry. *J. Chem. Educ.* **2023**, *100* (3), 1357–1365.
<https://doi.org/10.1021/acs.jchemed.2c00891>.
- (48) Eaton, A. C.; Delaney, S.; Schultz, M. Situating Sustainable Development within Secondary Chemistry Education via Systems Thinking: A Depth Study Approach. *J. Chem. Educ.* **2019**, *96* (12), 2968–2974. <https://doi.org/10.1021/acs.jchemed.9b00266>.
- (49) 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>.