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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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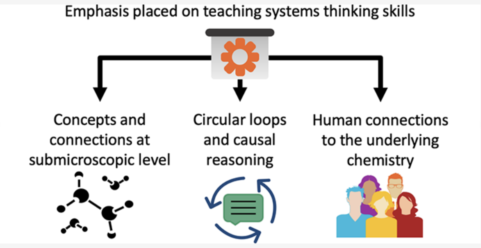
ABSTRACT: New resources have recently been emerging for educators to implement systems thinking (ST) in chemistry education, including a proposed set of ST skills. While these efforts aim to make ST implementation easier, little is known about how to assess these skills in a chemistry context. In this 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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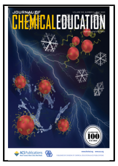

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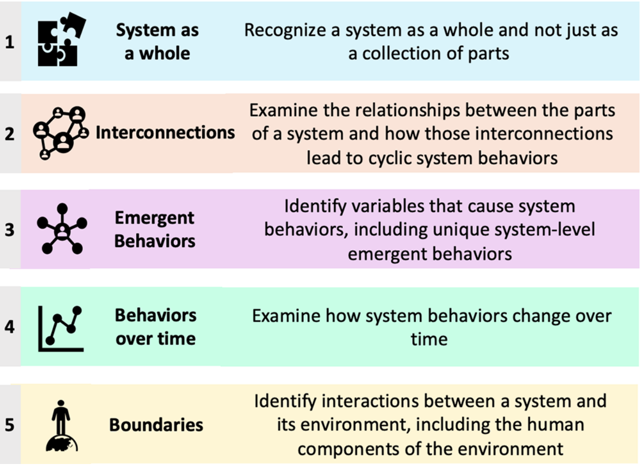
both analytical and holistic thinking: identifying and examining system components, their organization, causal factors, and system boundaries (analytical), as well as describing and interpreting system level behaviors, and interactions of the system with its environment (holistic).[23−27]

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 characteristics 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.



1	**System as a whole**	Recognize a system as a whole and not just as a collection of parts
2	**Interconnections**	Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviors
3	**Emergent Behaviors**	Identify variables that cause system behaviors, including unique system-level emergent behaviors
4	**Behaviors over time**	Examine how system behaviors change over time
5	**Boundaries**	Identify interactions between a system and its environment, including the human components of the environment

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

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.

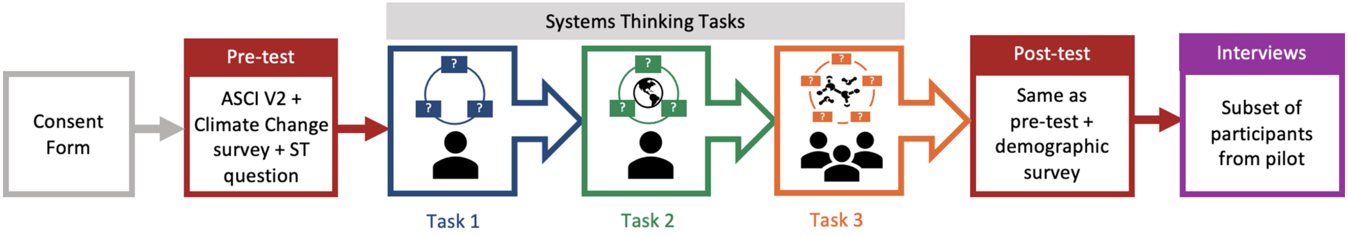


Figure 2. Design of the systems thinking intervention used in this study.

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]

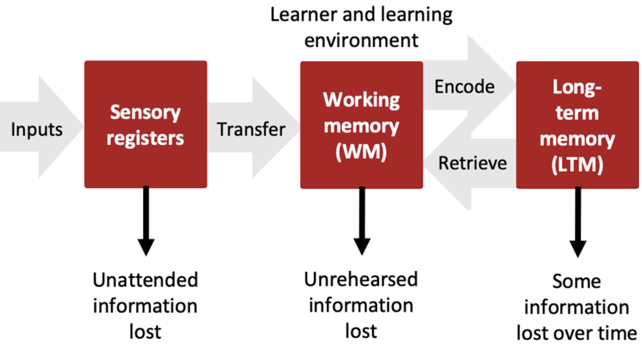


Figure 3. Model of modern information processing theory.

Researchers predict that when engaging in ST, each learner will activate a diverse range of prior knowledge from their memory beyond just chemistry knowledge.[1] 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

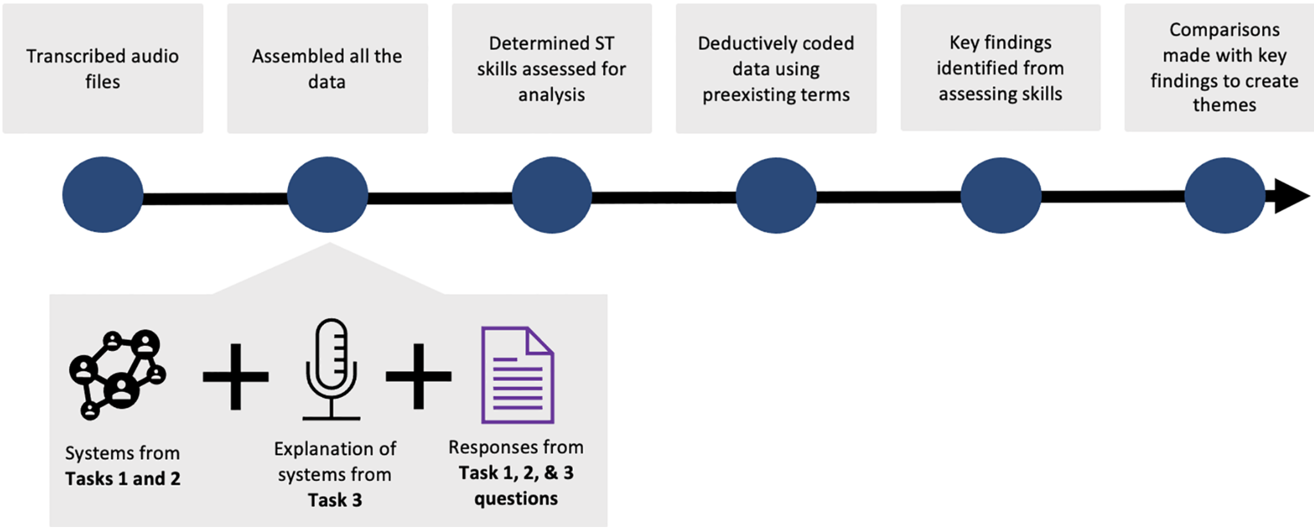
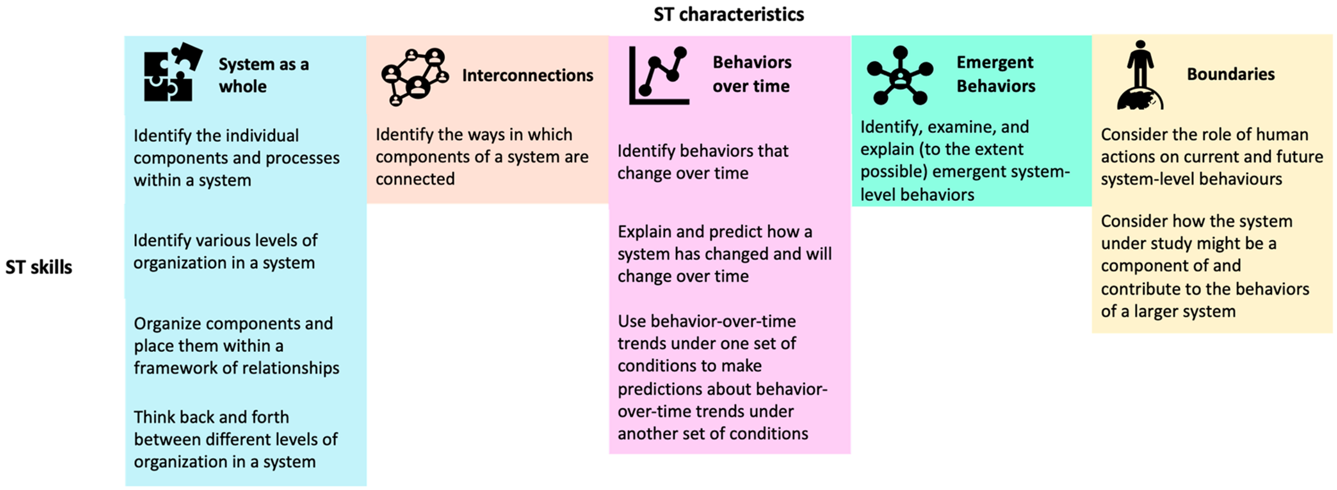


Figure 4. Overview of qualitative analysis procedure for ST study.



	ST characteristics				
	System as a whole	**Interconnections**	**Behaviors over time**	**Emergent Behaviors**	**Boundaries**
ST skills	Identify the individual components and processes within a 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 ways in which components of a system are connected	Identify behaviors that change over time Explain and predict how a system has changed and will change over time Use behavior-over-time trends under one set of conditions to make predictions about behavior-over-time trends under another set of conditions	Identify, examine, and explain (to the extent possible) emergent system-level behaviors	Consider the role of human actions on current and future system-level behaviours Consider how the system under study might be a component of and contribute to the behaviors of a larger system

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 being chemistry aligned with our study.[48] The society context is

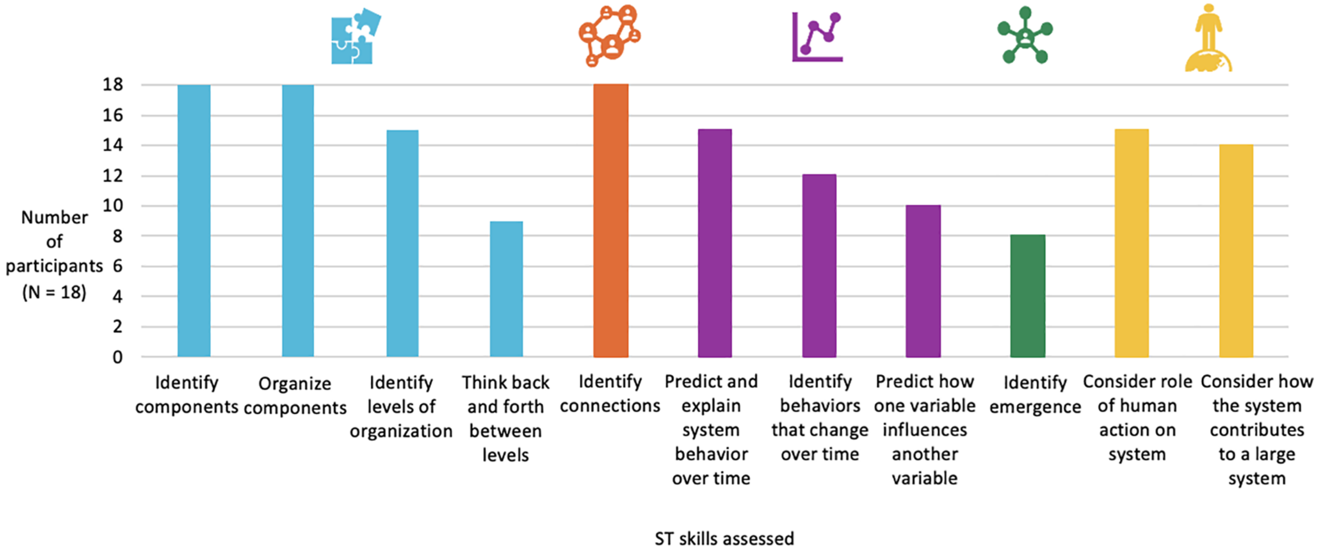


Figure 6. Systems thinking skills participants demonstrated when assessing the skills based on how they are worded from the literature.

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).

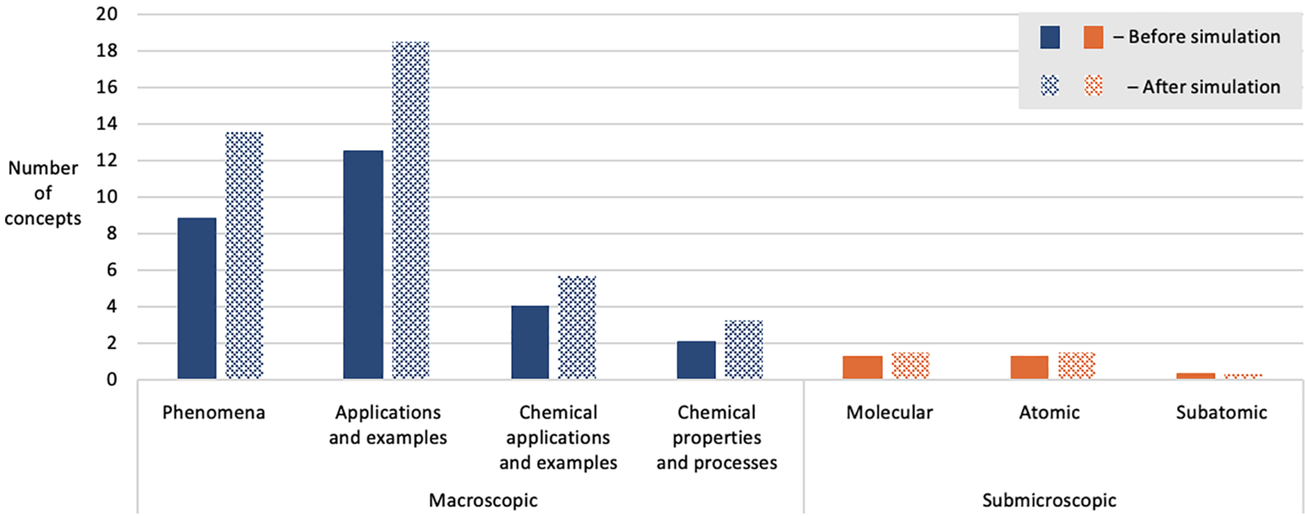


Figure 7. Seven levels of granularity associated with macroscopic and submicroscopic levels used to identify concepts present within students' system maps.

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

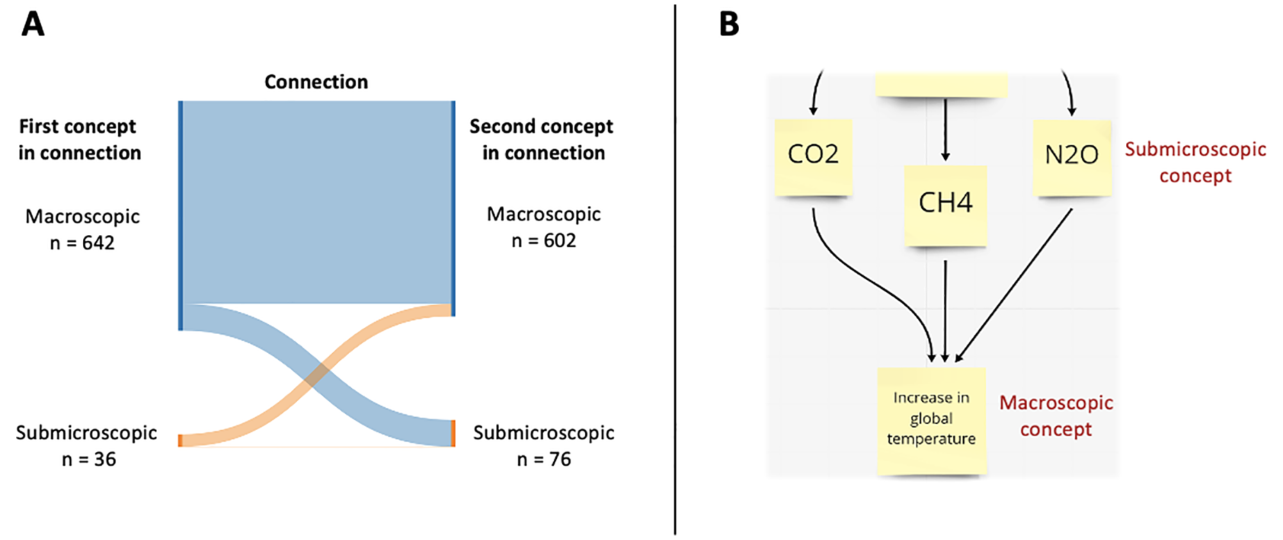


Figure 8. (A) A Sankey diagram indicating the number of connections made between the macroscopic and submicroscopic levels ($N = 678$). The left side of the Sankey diagram indicates the first concept in a connection and the right side is the second concept that it is connected (figure produced using 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 N_2O (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 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

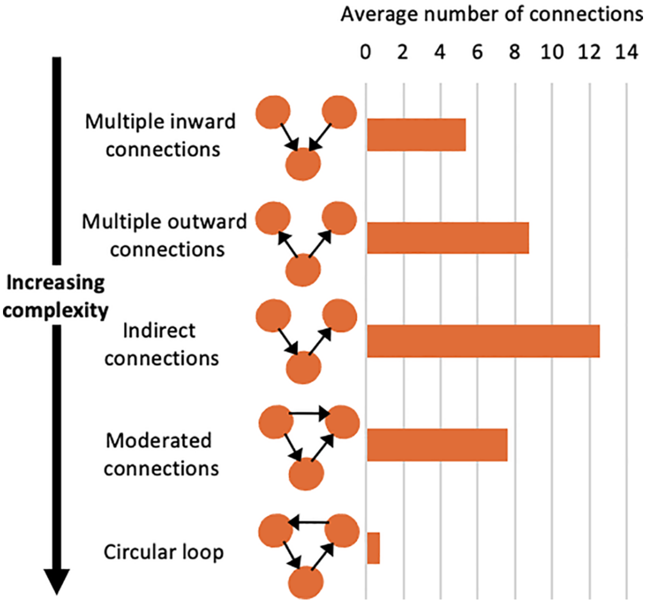


Figure 9. Average number of connections for each type of connection in participants' system maps.

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.

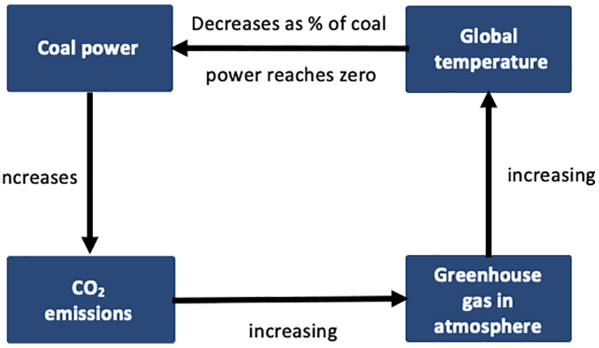


Figure 10. An example of a circular loop from a participant's system map.

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.

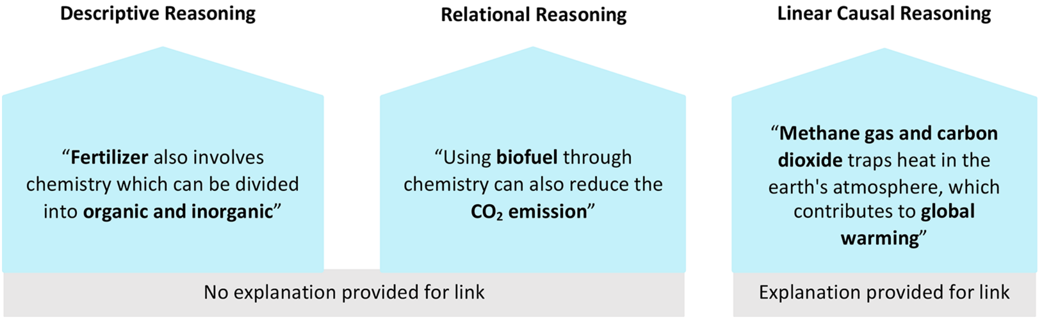


Figure 11. Examples of descriptive, relational, and linear causal reasoning of connections provided by participants; no examples of multicomponent causal reasoning were identified. Bolded words represent concepts in each connection.

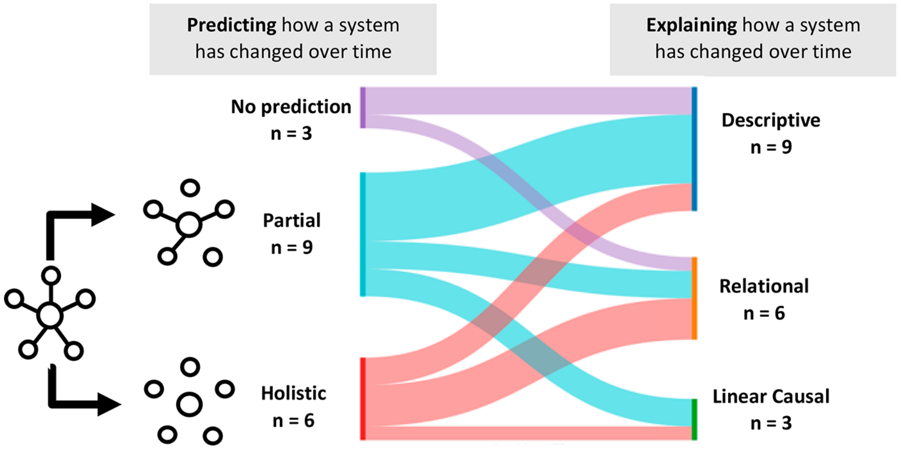


Figure 12. Ways participants predicted and explained how their systems changed over time; no examples of multicomponent causal reasoning were identified.

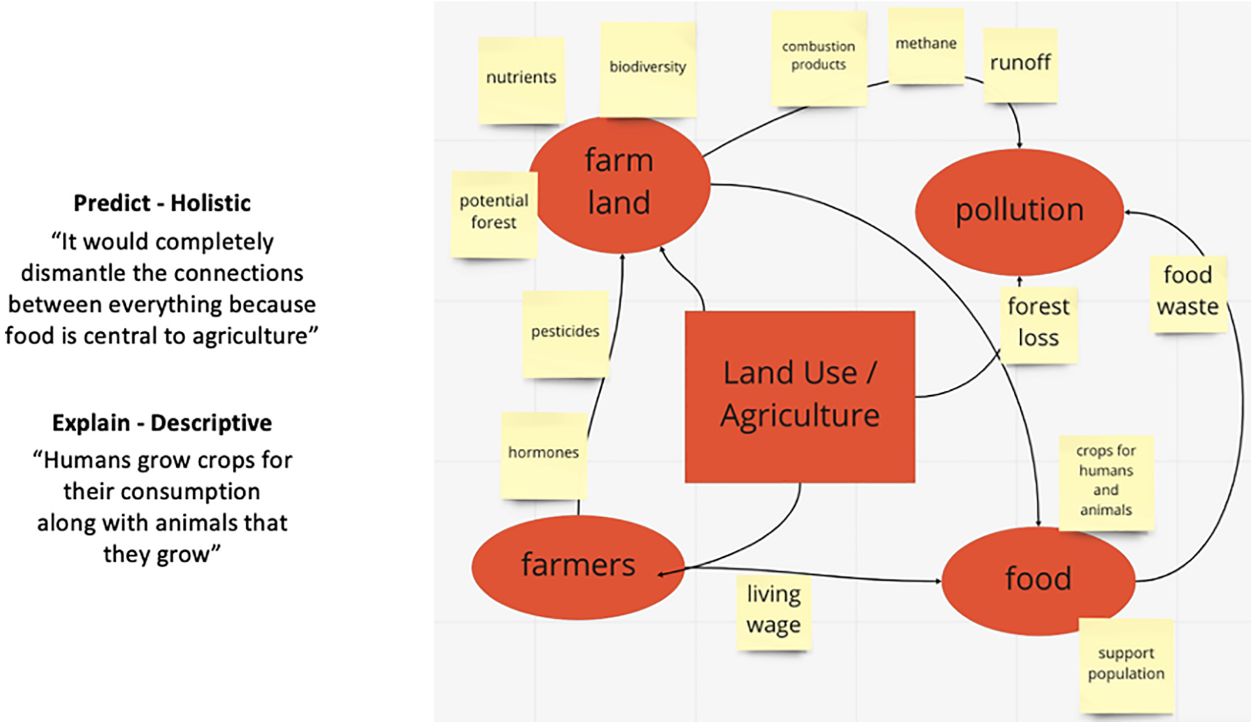


Figure 13. Example of a participants' (P12) system map including their prediction and explanation of how removing a concept would impact the rest of their system map. Food was the concept that this participant removed from their system.

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

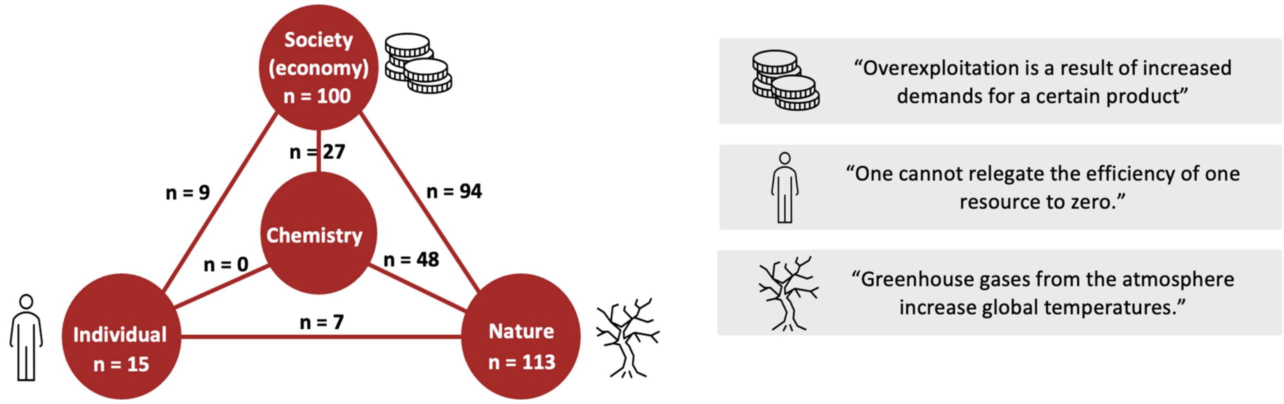


Figure 14. A triangular model of the aspects of environmental and sustainability issues adapted to include chemistry as a related context. Examples of participants' connections to the society, individual, and nature contexts are shown on the right side of the figure.

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

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 many connections to other contexts and/or disciplines.
	Includes limited chemistry connections to these 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.

[a] Note: 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

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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