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Curricular Innovations to Promote Systems Thinking in a General Chemistry Laboratory Course

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Abstract

Systems thinking is a perspective and set of skills used to examine the dynamic complexities of an entire system and to make predictions about system behavior. Systems thinking is of interest to educators because of its unique potential to enhance students' critical thinking and problem-solving skills, therefore developing scientists who are capable of addressing many of the complex problems facing our world today. Utilizing previously published pedagogical tools, revisions and additions that promote systems thinking were made to a general chemistry laboratory unit. Through these curricular innovations, students defined systems thinking and employed many systems thinking skills throughout the laboratory unit. Students were surveyed after completing the laboratory unit, and their responses were analyzed to assess the utility of the curriculum revisions and inform subsequent revisions.

Introduction

It is widely accepted that scientists operate within the context of a highly interconnected and dynamic world, most often focusing their investigations, even their entire careers, on the complexities of a singular system. Systems are characterized by a set of recurring themes: boundaries, components, interactions, functions, feedback, purpose, and cycles between equilibrium and chaos (Ho, 2019). The intricacies and significance of systems are easy to imagine when one considers even just a few examples: the human body, the economy, or plastic recycling. The ability to understand and contextualize systems is essential to making sense of our ever-changing and interwoven world.

The most pressing of contemporary scientific challenges are deeply rooted in complex systems; thus, the development and refinement of a robust systems thinking skillset is a necessary investment in the next generation of scientists. Arnold and Wade (2015) define systems thinking as a “set of synergistic analytical skills” that enhance system comprehension and recognition and are especially useful in predicting behavior or manipulating system behavior to a desired outcome (p. 675). Alternatively, York et al. (2019) describe systems thinking as a “holistic approach” that emphasizes the interconnection of system parts and their resulting patterns or behaviors (p. 2720). The exact definition of systems thinking has not reached consensus in academic circles, but in essence, systems thinking is the toolbox utilized to examine the dynamic complexities of an entire system and to make predictions about system behavior.

Gradually, students of science expand their knowledge of systems multidimensionally—they are exposed to new systems as their grasp on familiar systems becomes more thorough. Historically, educational systems achieve this learning outcome through a reductionist approach, the idea that complex systems can be understood solely through studying each of their component parts (Orgill et al., 2019; Fang & Casadevall, 2011). Reductionism has earned its role in the classroom by virtue of making complex scientific concepts more digestible, and many disciplines have employed this approach with great success. However, contemporary understanding of the emergent properties of dynamic systems has led to the conclusion that systems are more than the sum of their parts; therefore, extrapolations from the pieces to the whole cannot be made reliably. Much like a puzzle piece does not accurately depict a puzzle’s picture, neither can a components’ behavior be expected to predict system behavior. Relying solely on a reductionist approach, students often struggle to apply their knowledge to our interconnected world; systems thinking is one tactic for addressing this difficulty. Systems thinking is not designed to replace reductionist methods of teaching and learning, but should instead complement them (Orgill, et al. 2019).

Systems thinking has been widely acknowledged as the next step for science education because of its ability to enhance students' critical thinking and problem-solving skills while increasing topic engagement. A systems thinking approach for the chemistry classroom is "context-based," linking curricular topics and ideas to global challenges that feel relevant to students (Talanquer, 2019). Adjusting the lens through which chemistry is taught—changing the emphasis from the pieces to the system—can have a tremendous impact on student learning. Pazicni and Flynn (2019) assert that a deeper understanding of chemistry is facilitated by systems thinking skills through the ability to provide holistic and transferable knowledge. Systems thinking skills are nurtured in the classroom through model building, concept map design, behavior prediction, or analysis of knowledge boundaries while incorporating environmental, social, and economic influences (Jegstad & Sinnes, 2015). For these reasons, a systems thinking approach to activities and lessons naturally creates space for collaboration, discussion, and reflection, which has been theorized to positively impact student learning and engagement (Jacobson & Wilensky, 2006). And yet, learning about systems poses special challenges; complex systems are cognitively taxing due to their expansive nature and convoluted interactions (Hmelo-Silver & Azevedo, 2006). Therefore, integrating systems thinking effectively requires an intentional and tailored approach.

Although benefits of teaching systems thinking have been well-characterized, wholly incorporating systems into introductory classes remains a daunting task for educators. Often, the development process places a huge burden on educators as it involves extensive research on systems that are beyond the scope of a typical introductory course. Furthermore, to incorporate systems thinking successfully, educators must identify relevant opportunities for inclusion of illustrative systems, design questions or activities, and ensure cognitive load is manageable for students. Luckily, materials have been developed that help educators kickstart this process.

The Characteristics Essential for Designing or Modifying Instruction for a Systems Thinking approach (ChEMIST) table, a tool developed for the evaluation and design of new systems thinking curriculum, maps pillars of systems thinking to demonstrable skills (York & Orgill, 2020). Designed for educators, the table proves useful for identifying systems thinking opportunities in existing chemistry curricula.

Additionally, the Systems Thinking Hierarchical Model provides instructors with a visual representation of sequentially developed systems thinking skills (Orion & Ben-Zvi-Asser, 2010; Orgill et al., 2019). This graphic can serve as a baseline for building curriculum with the essential steppingstones to high-order systems thinking skills, which are depicted in Figure 1.

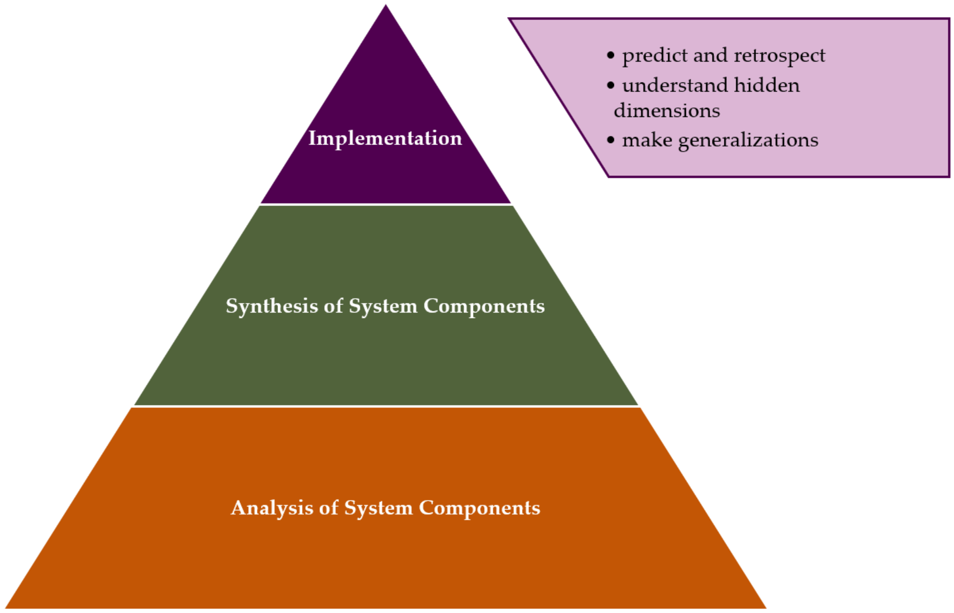

Figure 1 Adapted version of the Systems Thinking Hierarchical Model pyramid (Orgill et al., 2019). Descriptions of Implementation sublevels are provided to the right of the pyramid.

Given the importance of systems thinking in the chemical sciences, we sought to redevelop the general chemistry laboratory experience according to the following pedagogical aims:

- Intentionally cultivate students' systems thinking skills, with emphasis on higher-order skills
- Explicitly introduce the concept and definition of systems thinking
- Effectively communicate the importance of being a system-knowledgeable and system-oriented scientist

Using the aforementioned educational tools, areas in the general chemistry laboratory curriculum where systems thinking could be enhanced were identified. Based on this assessment, existing homework assignments were revised and an entirely new activity focused on the pedagogical aims stated above was designed. Finally, student responses to the new materials were analyzed and a survey was administered in order to gain insights that could be used to inform and further refine future instruction.

Methods

Instructional Context

Students enrolled in General Chemistry II lecture and laboratory at Seattle University participated in the revised laboratory experience. In Winter Quarter and Spring Quarter, there were 85 and 29 student participants, respectively.

General Chemistry laboratory units typically consist of three components: pre-lab questions, in person laboratory experience, and post-lab reflection questions. The purpose of post-lab reflection questions is to prompt students to engage more deeply with concepts and skills developed in the lab and to connect them to their broader learning context in chemistry.

Evaluation of Existing Activities

The first step in the revision process was to analyze existing instructional materials for characteristics of systems thinking using the ChEMIST table (York & Orgill, 2020). If questions did not prompt systems thinking in their current form, they were categorized as such. If questions were determined to prompt systems thinking, they were linked to one or more of the skills on the ChEMIST table and were ranked on a scale from "less holistic, more analytical" to "more holistic, less analytical." Questions that were determined not to prompt systems thinking or fell into the "less holistic, more analytical" category then became targets of improvement and were workshopped to emphasize more systems thinking skills.

Revisions

Curricular revisions were executed by two chemistry educators and an undergraduate researcher. The goals of the revision were to better support students' development of systems thinking skills and to explicitly introduce students to the concept of systems thinking. Using the process above, an appropriate laboratory unit was decided upon. This unit analyzed Seattle municipal tap water samples, allowing for natural integration of systems thinking instruction into an existing lab experience. In this Water Quality Analysis unit, students were tasked with measuring the temperature, chlorine content, conductivity, pH, alkalinity, and hardness of tap water. Because these characteristics are influenced by the larger context of the Seattle municipal water system and the seasonal water cycle, this lab provided a clear opportunity to help students uncover the underlying systems at work. Two major changes were made to the Water Quality Analysis unit:

- Existing post-lab reflection assignments were edited to intentionally target systems thinking skills.
- A guided inquiry activity was developed to explicitly engage students with the topic of systems thinking. Students completed this activity during the second laboratory period of the unit.

Refer to Figure 2 for contextualization of these laboratory components into the unit schedule.

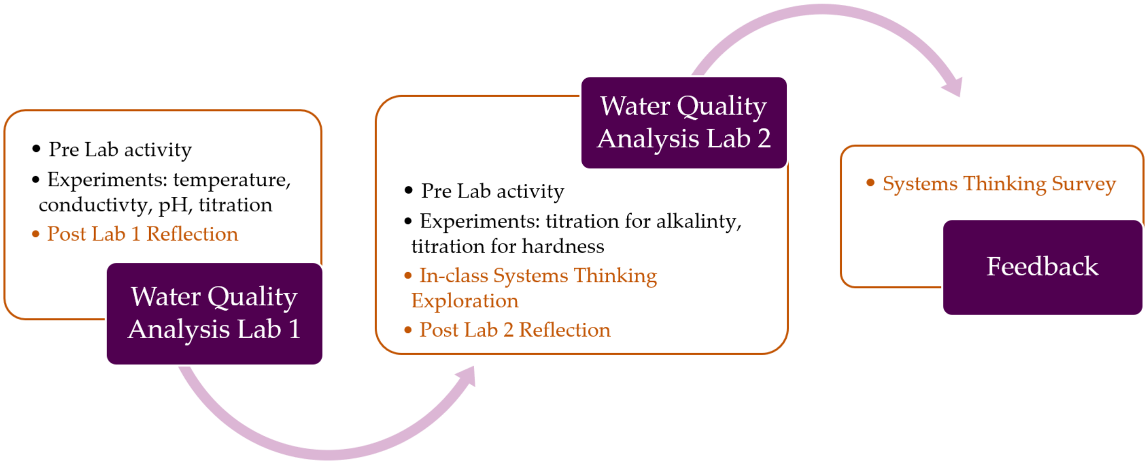

Figure 2 Laboratory unit schedule and description of events, with new or revised components indicated in orange.

<u>Revision by Systems Thinking Hierarchical Model</u>

To revise existing questions, the Systems Thinking Hierarchical Model (Orgill et al., 2019) was utilized as a framework. Frequently, questions identified for revision demonstrated skills represented in the "Analysis of System Components" level of the pyramid. From there, either the synthesis or implementation region was chosen as a target outcome. The descriptive categorization, provided by the sublevel descriptions included in the Systems Thinking Hierarchical Model (Orgill et al., 2019), inspired further structure for question revision. The ChEMIST table (York & Orgill, 2020) was used as needed to provide concrete examples of behaviors that model systems thinking skills.

<u>Design of a POGIL-like Activity: Systems Thinking Exploration</u>

To contextualize the reorientation of the lab toward more and higher-order systems thinking skills, a guided inquiry activity utilizing the learning cycle was designed to introduce students to the definition of systems thinking. An exploration of systems thinking was designed with the Process Oriented Guided Inquiry Learning (POGIL) model in mind, which uses a model, or figure, to direct students through a learning cycle (Simonson, 2019, p. 9). The format and question progression were based on the classical pillars of POGIL: exploration, concept invention, and application. Thus, the activity was designated "POGIL-like" (Simonson, 2019).

Instructional Implementation and Data Analysis

Five faculty, including one co-author, were involved in facilitating the activity over two quarters of general chemistry laboratory, which were held Winter and Spring Quarter of 2022. After initial implementation and response review from Winter Quarter 2022, revisions to the activity were made for Spring Quarter 2022. A summary of these edits and revisions can be found in the Results and Discussion section.

Student Perception Survey

A Likert scale survey was used to assess students' perceptions of the revised laboratory unit. In total, 91 students participated across two academic quarters. Questions were used to evaluate previous exposure to systems thinking, perceived relatedness of systems thinking to the Water Quality Analysis lab, and relevance of systems thinking to students and scientists.

Thematic Analysis of Student Responses to New Activity

To better understand how the new guided inquiry activity functions to support students' understanding of systems thinking, thematic analysis of student responses to the following selected questions was performed:

- With the knowledge that systems thinking emphasizes the importance of the upper levels (A, B, C, etc.) of the pyramid, can you deduce the definition of systems thinking?
- Why is systems thinking an especially important skill for chemists and biologists?
- What is an example of a topic from class that required you to understand the cyclic nature of systems?
- In your experience, what do you need to know about a system to make a prediction about its future behavior?

Each of the three authors independently analyzed student responses for emergent themes. The authors iteratively discussed results from individual analyses until a common set of themes emerged.

Human Subjects Oversight

The Seattle University Institutional Review Board has determined the study to be exempt from IRB review in accordance with federal regulation criteria.

Results and Discussion

Given the importance of systems thinking for future scientists and healthcare professionals, we sought to enhance students' awareness of and engagement with systems thinking skills in the general chemistry laboratory curriculum. To accomplish this goal, we started by using previously published tools to critically evaluate an existing laboratory unit using a systems thinking lens. Having identified areas to improve systems thinking awareness and skills within the unit, we revised existing questions, added new questions, and designed a new guided inquiry activity to be included as part of the laboratory unit. The revised laboratory unit was implemented in five lab sections. Student responses to activity questions and a survey were analyzed in order to understand strengths of the curricular changes and areas for improvement. Finally, a second round of revisions were made in response to the data analysis and revised materials and were subsequently used in two lab sections. The following section provides a detailed description and analysis of the curricular revisions made.

Evaluation of Existing Activities

As described in the methods section, the ChEMIST table was used to categorize each existing post-lab question according to the analytical–holistic spectrum of systems thinking skills. As a result of this analysis, one question was added to the Post Lab 1 Reflection and one question was edited. Six questions were added to the Post Lab 2 Reflection. All new and edited questions aimed to better develop students' high-order systems thinking skills. A complete version of the ChEMIST table analysis and curricular revisions can be found in Appendix A and Appendix B, respectively. Selected examples are described in detail below.

Revisions

Post Lab 1 Reflection

In the original Post Lab 1 Reflection, students were given the typical ranges of ground and surface water conductivity, then asked to extrapolate the source of Seattle tap water based on their measured conductivity data. First, we identified that skills required to complete this question mapped to the essential ChEMIST table characteristic of "Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviors" (York & Orgill, 2020). However, answering this question only required simple comparison of measured and reported values, so we determined it to be less holistic and more analytical. Steps were taken to elevate the level of systems thinking skills required to successfully complete the assignment. The final product was an expansion into two questions—one leading question (revision [R] in Table 1) and one holistic question (insertion [I] in Table 1). Detailed description of curricular improvements can be found in Appendix B. Systems thinking skills targeted before and after revisions are highlighted in Table 1 below.

Table 1 Post Lab 1 Reflection improvements mapped onto an adapted version of the ChEMIST Table (York & Orgill, 2020). Revisions and Insertions are represented by R and I, respectively, while newly represented systems thinking skills are marked with stars and those that were elevated by revision are represented by arrows. Reprinted (adapted) with permission from York, S., & Orgill, M. (2020). ChEMIST table: A tool for designing or modifying instruction for a systems thinking approach in chemistry education. *Journal of Chemical Education, 97*(8), 2114-2129. https://doi.org/10.1021/acs.jchemed.0c00382. Copyright 2020 American Chemical Society.

	Systems Thinking Skills		
Essential Characteristics	**Less Holistic** (more analytical)		**More Holistic** (less analytical)
Recognize system as a whole, not just as a collection of parts	Identify the individual components and processes within a system	R 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 behaviors	Identify the ways in which components of a system ★ R are connected	Examine positive and negative feedback loops within a system	Identify and explain the causes of cyclic behaviors within a system
Examine how system behaviors change over time	I Identify system-level behaviors that change over time	Describe how a given system-level behavior changes over time R	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

<u>Post Lab 2 Reflection</u>

Insertion 1. Edits to this section focused on developing students' ability to analyze the cyclic nature of systems. Seven entirely new, sequential questions were added and two were deleted. In-depth analysis of Seattle Public Utilities (SPU) publicly available water quality data revealed a seasonal trend in the alkalinity measurements (City of Seattle, 2022). Scientists at SPU confirmed that the trend has natural origins, so pedagogical content was designed around the connection between seasonal cycles and alkalinity. Elevation of cyclic systems thinking skills through assignment revision can be tracked in Table 2. Appendix B reports the series of questions developed.

Insertion 2. A more straightforward approach to utilize higher-order systems thinking skills was used in the next question where students were asked to recognize a "hidden dimension" of the system. In their responses, students noted various examples, including wastewater treatment, pollution, rain acidity, climate changes, and the properties of the pipes that distribute municipal water.

Insertion 3. Finally, to serve as a reflection and an explicit connection to the Systems Thinking Activity that was completed during the laboratory period, students were again shown the Systems Thinking Hierarchical Model and asked to identify a skill from the model that they used in the reflection assignment. A summary of the skills they identified is reported in Figure 3. The most reported response was the "ability to understand cyclic nature of systems," which falls under the broader "synthesis" skills in the pyramid. This reflects the corresponding aim we hoped to target, which promotes the belief that students are absorbing ChEMIST table content; however, these responses could be attributed to the investigation of cyclic trends in the preceding questions. "Hidden dimensions" as a popular response is unsurprising because it was mentioned explicitly during the activity. Identifying relationships was also a common response, unsurprisingly, as this activity included proposing relationships between alkalinity and conductivity, water availability and season, and alkalinity and dam passage of water.

Design of a POGIL-like Activity: Systems Thinking Exploration

Two main pedagogical goals guided the development of the activity. First, students were prompted to produce the definition of systems through a learning-cycle investigation of the model. Afterward, students would deepen their understanding of systems thinking skills by exploring their association to a real-world model. This activity, which can be found in its entirety in Appendix C, was implemented during the Water Quality Analysis Lab 2 period, after students had been prompted to consider a municipal water system as part of the Post Lab 1 Reflection. Refer to Figure 2 for a visual aid of the chronological systems thinking exposure from student perspective, with curricular additions and revisions included in orange.

Table 2 Post Lab 2 Reflection improvements mapped onto an adapted version of the ChEMIST Table (York & Orgill, 2020). Reprinted (adapted) with permission from York, S., & Orgill, M. (2020). ChEMIST table: A tool for designing or modifying instruction for a systems thinking approach in chemistry education. *Journal of Chemical Education, 97*(8), 2114-2129. https://doi.org/10.1021/acs.jchemed.0c00382. Copyright 2020 American Chemical Society.

	Systems Thinking Skills		
Essential Characteristics	**Less Holistic** (more analytical)		**More Holistic** (less analytical)
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	Examine positive and negative feedback loops within a system	Identify and explain the causes of cyclic behaviors within a system

Revision of POGIL-like Activity Based on Student Responses

After receiving Winter Quarter data, student responses were analyzed and the activity was updated. Confusion about the distinction between the terms "regions" (i.e. analysis, synthesis, and implementation) and "levels" (the explicit skills) in the pyramid was common in responses, so the pyramid figure was labelled, and the questions were revised to more clearly reflect the updated figure. Additionally, the following question was added to subtly remind students of the critical reductionist learning outcomes that serve as building blocks for systems thinking skills:

> As you explored in Question 2, the systems thinking model is depicted as a pyramid because each level is contingent on the skills below. In an introductory course like general chemistry, what part of the pyramid would you expect to focus on?

For ease of distribution and data collection, the activity was adapted from a paper handout to a Canvas quiz. On the application problems, students now had to select one representative skill from a dropdown, whereas on paper they could identify a variety of targeted systems thinking skills. This adjustment limited the variability in student responses, but overall trends stayed consistent.

Student responses to the survey administered at the end of Winter Quarter also informed revisions. Evaluations of the usefulness of systems thinking varied greatly between sections. When asked if systems thinking was critical to understanding chemistry, students in one lab section had a notably higher response of "strong agreement" (64% "strong agreement" compared to the average across sections of 35%). After discussing these findings with this section's facilitator, we were able to identify two factors that were likely influential: familiarity level with facilitating POGIL-like activities and the utilization of first-hand research examples. In response, a robust facilitation guide was developed to provide direction for instructors and improve consistency across lab sections. This guide, which can be found in Appendix D, included a brief background on and formal definition of systems thinking, a typical structure for POGIL-like activities, and direction for facilitators to prepare personal examples of ways they've relied on systems thinking skills during their careers.

Data Analysis

The following thematic analysis and survey analysis deal with data combined for both quarters, unless otherwise mentioned.

Thematic Analysis of the POGIL-like Activity: Systems Thinking Exploration

Thematic analysis of student responses to the concept invention question and a selection of the application questions (Table 3) revealed that overall, students were fairly good at identifying the core pillars of systems thinking. Specifically, many students recognized the emphasis on relationships between parts and the importance of these skills for understanding systems. Most answers fell under three overarching themes: orientation tool, metacognitive tool, and predictive tool.

Orientation Tool. Students acknowledged uses for systems thinking that included characterizing the whole system versus components, getting to know the system, and exploring complexities. In essence, these applications of systems thinking are ways that systems thinking can be used to orient oneself with the system. Students also noted that systems thinking skills are essential for predicting future system behavior.

Metacognitive Tool. Students recognized systems thinking as a tool for assessing their own knowledge of a system, or a metacognitive tool. They proposed that systems thinking could be used to identify gaps in knowledge or areas for improvement. The frequency of this response could be due to the format of the application questions in the activity, where students were given hypothetical scenarios and asked to identify the skills of the pyramid that were utilized.

Predictive Tool. Students defined systems thinking as the skillset required for making predictions about a system. This response again could be attributable to the design of the activity. The question asking students to define systems thinking explicitly tells students that "systems thinking targets the upper levels of the pyramid," and one of the skills in the implementation section of the pyramid is "prediction."

Table 3 Themes and sample responses identified for select questions on the Systems Thinking Exploration.

Question	Common Response Themes	Sample Response
With the knowledge that systems thinking emphasizes the importance of the upper levels (A, B, C, etc.) of the pyramid, can you deduce the definition of systems?	Metacognitive tool	"ST is used to deduce your level of understanding and advance it"
	Predictive tool	"ability to apply known aspects of the system in a broader sense and use those applications to predict future system behavior"
	Orientation tool	"A method of analysis that organizes individual components of a system to better understand the structure, relationships, and trends of said system"
Why is systems thinking an especially important skillset for chemists and biologists?	Real systems are connected beyond memorized pieces	"Because organisms and ecological environments are made up of systems. Also, [chemists and biologists] need to be able to apply their basic knowledge to new situations."
	Helps digest real world complexity	"…knowing how to apply what you learning lectures in lab to real life"
	Reflects the scientific process	"[they] need to understand exactly what they're analyzing to create more accurate hypotheses."
In your experience, what do you need to know about a system to make a prediction about its future behavior?	Relationship between parts	"How each part works, which part influences the others, and which way the cycle or direction of a process goes"
	Past behaviors and patterns	"You need to know its past behavior, its deviations from the norm, and what causes these deviations.

Survey

A survey was developed to assess progress toward the project goals. The following Likert Scale questions (I–V) and free response questions (VI–IX) were included:

I. I was familiar with the term "systems thinking" before studying it in the context of the Water Quality Analysis lab and associated activities and assignments.
II. The Water Quality Analysis lab helped me strengthen my systems thinking skills.
III. Systems thinking allowed me to better understand the chemistry concepts covered in the Water Quality Analysis lab.
IV. I believe systems thinking is critical to understanding chemistry.
V. Systems thinking skills are necessary for contemporary scientists.
VI. If you have been introduced to the term "systems thinking" previously, what was the context? If not, please respond with N/A.
VII. What concepts or classes could be enhanced by applying systems thinking?
VIII. Where do you foresee yourself applying systems thinking skills in the future?
IX. Do you have any feedback about the Water Quality Analysis lab and accompanying systems thinking activity?

Student Likert scale responses to questions I–V are summarized in Figure 4. The survey was administered optionally, yielding N=91 participants total across both quarters of instruction. The Winter Quarter cohort was much larger (N=66) than the Spring Quarter cohort (N=25), so data were combined for analysis purposes unless otherwise stated.

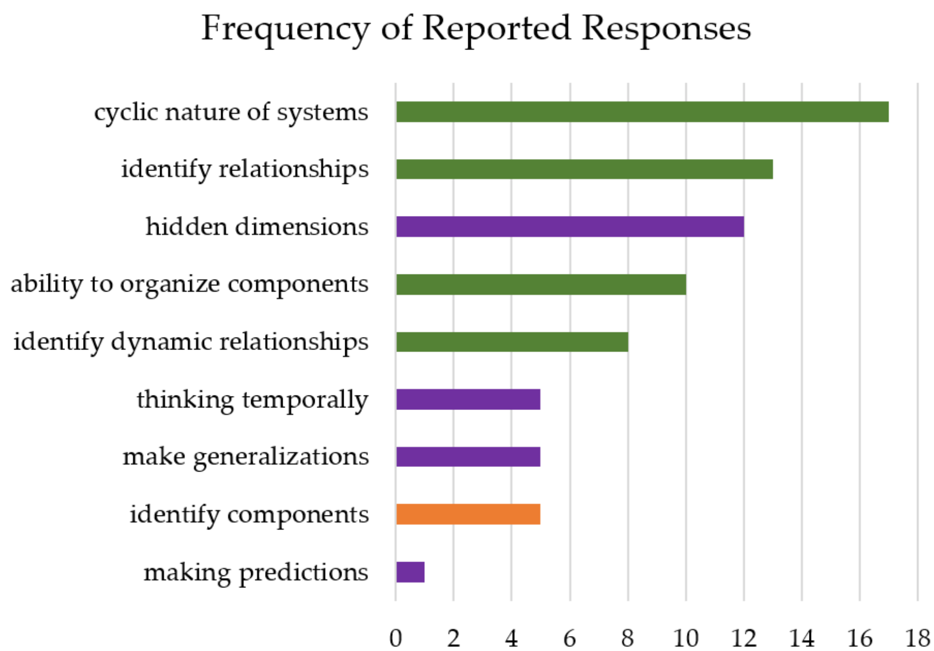

Figure 3 Number of times the following systems thinking skill was identified in response to the activity. Responses that did not name a specific skill were excluded, resulting in N=76. Purple, orange, and green represent skills associated with the respectively labelled levels in Figure 1, with purple representing highest-order systems thinking skills.

When asked for feedback on the activity (question IX), some students noted the Systems Thinking Exploration felt like common sense; however, only 10-20% of students reported familiarity with systems thinking (question I). Of those who reported familiarity, previous exposure was noted (question VI) mostly in previous science classes, particularly biology. A sense of familiarity with systems thinking could be evidence that context-based education in the sciences is becoming more prominent; increased practice and exposure to systems builds the foundation for systems thinking regardless of explicit introduction.

Of all students who participated in the activity, nearly 83% acknowledged that participating in the Water Quality Analysis lab strengthened their systems thinking skills (question II). Students' previous exposure to the Systems Thinking Hierarchical Model pyramid and their practice applying systems thinking skills make them credible assessors at the point of taking the survey. Thus, this reflects positively on our first aim: to intentionally develop more and higher-order systems thinking skills. Positive evaluation on this survey question coupled with a use of self-identified systems thinking skills (Figure 3) serves as evidence that students' growth as systems thinkers was facilitated by practice with mid- and high-level systems thinking skills during this laboratory module. General approval of the question II statement reinforces the idea that students respond well to systems-based and real-world examples.

In the Winter Quarter cohort, 69% of students believed systems thinking was an asset to their understanding of the chemistry concepts covered in the laboratory unit (question III). After revisions, the Spring Quarter cohort reported 100% agreement or strong agreement. Based on this improvement, we deduce that the revisions positively impacted student experience. Overall, responses indicate comprehension of the importance of systems thinking to solving complex problems like the ones posed.

The importance of being a system-knowledgeable and system-oriented scientist was communicated effectively through the activity, as evidenced by more than 80% of students agreeing or strongly agreeing that systems thinking is critical to understanding chemistry (question IV). Many students pursue science because of the promise of positively contributing to integrated system problems like healthcare inequity, pollution, or clean and renewable energy. Although students recognize the importance of systems in science, the majority of these students had not heard of "systems thinking." Now, with a definition in hand, they do affirm the importance of the skillset. Our second goal of providing language made this possible. Between Winter and Spring Quarter, there was a large increase in students "strongly agreeing" with the statement, from 34% to 48%. Every student (100%) in the spring cohort "agreed" or "strongly agreed" that systems thinking skills are necessary for contemporary scientists (question V). This was a large improvement over the roughly 85% in the previous quarter. Curricular revisions and the addition of the implementation guide are theorized to be the cause of these improvements in student evaluation.

Further, students could envision themselves applying systems thinking skills across broad horizons of scientific domains. When asked which concepts or classes could be enhanced by systems thinking (question VII), each of the following was mentioned by name at least once: mathematics, physics, biology, environmental science, computer science, "STEM" in general, and any class with a laboratory component. Students recognize the integral nature of systems to science. Students were easily able to think of situations where they will use systems thinking in the future (question VIII), including but not limited to the medical field or other work sectors, current events, coding (model building), future research, and college- or career-related projects.

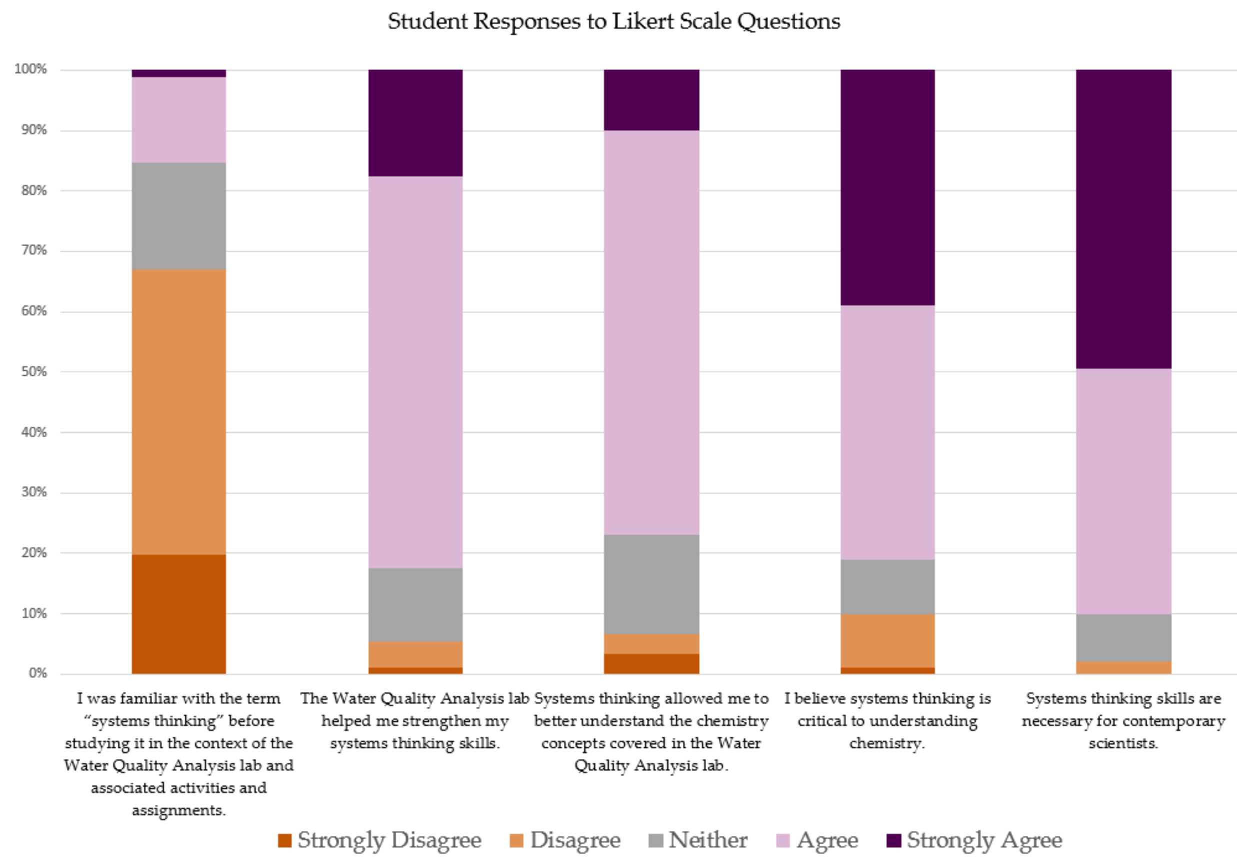

Figure 4 Summary of student responses to Likert questions included on survey (N=91).

Conclusion

In this study, we modelled how previously published tools can be used to support curricular revision and novel implementation of an activity designed to develop systems thinking knowledge and skills in General Chemistry laboratory. As such, the processes described here can serve as a guidebook for educators interested in designing systems thinking activities for their classrooms or laboratories. Furthermore, instructors are called to use and adapt our guided learning activity, the Systems Thinking Exploration, which can be useful in a variety of disciplines at the instructor's discretion.

Using previously published tools, the ChEMIST table and the Systems Thinking Hierarchical Model pyramid, we identified areas in a General Chemistry laboratory unit where systems thinking could be enhanced, resulting in a series of revised and new post-lab questions and a new guided inquiry activity. All new and revised materials sought to enhance three pedagogical goals: 1) intentional development of students' systems thinking skills, 2) explicit introduction of systems thinking, and 3) effective communication of the importance of being a system-knowledgeable and system-oriented scientist. Progress towards each of these pedagogical goals is summarized below.

Intentional Development of Students' Higher Order Systems Thinking Skills

All new and revised materials are intended to prompt students to put systems thinking skills into action. Evaluation of new and revised questions using the ChEMIST table suggests that students are prompted to engage in systems thinking through completing the revised Water Quality Analysis unit. Furthermore, survey results indicate that the vast majority of students (82.4%) agreed that their systems thinking skills had been developed through the course of completing the laboratory experience.

Explicit Introduction to the Concept and Definition of Systems Thinking

With less than 15% of students noting past introduction to the term "systems thinking," explicitly introducing all general chemistry students to the term and definition marks a significant gain. Thematic analysis of student responses to the Systems Thinking Exploration shows that, in general, students arrived at a relevant and meaningful definition of systems thinking.

Communicate the Importance of Being a System-Knowledgeable and System-Oriented Scientist

By the time of survey implementation, 81% of students subscribed to the belief that systems thinking skills are necessary for contemporary scientists. Students' ability to recognize a wide variety of fields, careers, and classes that could utilize systems thinking speaks to success in regard to this aim. Notably, students also agreed that systems thinking improved their understanding of chemistry concepts, which speaks to the utility of systems thinking in reinforcing foundational knowledge.

Future Directions

Although evidence presented indicates progress towards stated pedagogical goals, improvements can be made in order to more fully support students in developing systems thinking skills. In the way the water system is defined in our lab, water is only investigated at its natural source and its municipal source. In the current activity, students are not prompted to investigate the process by which wastewater returns to the natural system. As a result, our students are not investigating a complete system. In future iterations, we should define the water system in the water quality laboratory activity as beginning and ending at the natural source. By broadening these restrictive system boundaries, our activity can better represent "system-like" behavior. For example, alkalinity and conductivity, while exhibiting cyclical behaviors, do not demonstrate regulatory behaviors or feedback responses as system elements typically do. When we consider the complete system, we can likely find examples of feedback regulation and other emergent characteristics within our water system.

To close the loop on our water quality lab activity, there is opportunity to prompt students to consider the fate of water after it is poured back down the drain. This could be connected to wastewater treatment, return of water into the Puget Sound, and even evaporation through the water cycle. Connecting back to the ecological and environmental impacts of our own human interaction with the water system would draw attention to an important systems thinking characteristic in the ChEMIST table that we have not yet addressed: "identifying the interactions between a system and its environment, including the human components of the environment" (York & Orgill, 2020).

Going forward, we plan to apply this approach to other aspects of the chemistry curriculum at our institution and encourage others to do the same. An unintended positive impact of this project was the exposure to systems thinking many chemistry faculty received through facilitation of the guided inquiry. This serves as a strong network to rely upon for our next goal: we plan to explore how the new Systems Thinking Exploration functions in other course contexts in an attempt to intentionally build systems thinking across the chemistry curriculum.

References

Arnold, R. D., & Wade, J. P. (2015). A definition of systems thinking: A systems approach. *Procedia Computer Science, 44*, 669-678. https://doi.org/10.1016/j.procs. 2015.03.050

City of Seattle. (2022). *Water Quality Annual Reports*. Seattle Public Utilities. Retrieved from https://www.seattle.gov/utilities/about/reports/water-quality

Fang, F. C., & Casadevall, A. (2011). Reductionistic and holistic science. *Infection and Immunity, 79*(4), 1401-1404. https://doi.org/10.1128/IAI.01343-10

Hmelo-Silver, C. E., & Azevedo, R. (2006). Understanding complex systems: Some core challenges. *Journal of the Learning Sciences, 15*(1), 53-61. https://doi.org/10.1207/s15327809jls1501_7

Ho, F. M. (2019). Turning challenges into opportunities for promoting systems thinking through chemistry education. *Journal of Chemical Education, 96*(12), 2764-2776. https:// doi.org/10.1021/acs.jchemed.9b00309

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *Journal of the Learning Sciences, 15*(1), 11-34. https://doi.org/10.1207/s15327809jls1501_4

Jegstad, K. M., & Sinnes, A. T. (2015). Chemistry teaching for the future: A model for secondary chemistry education for sustainable development. *International Journal of Science Education, 37*(4), 655-683. https://doi.org/10.1080/09500693.2014.1003988

Lee, A., & Liew, M. S. (2021). Tertiary recycling of plastics waste: An analysis of feedstock, chemical and biological degradation methods. *Journal of Material Cycles and Waste Management, 23*(1), 32-43. https://doi.org/10.1007/s10163-020-01106-2

Orgill, M., York, S., & MacKellar, J. (2019). Introduction to systems thinking for the chemistry education community. *Journal of Chemical Education, 96*(12), 2720-2729. https:// doi.org/10.1021/acs.jchemed.9b00169

Orion, N., & Ben-Zvi-Assaraf, O. (2010). Four case studies, six years later: Developing system thinking skills in junior high school and sustaining them over time. *Journal of Research in Science Teaching, 47*, 1253-1280. https://doi.org/10.1002/tea.20383

Pazicni, S., & Flynn, A. B. (2019). Systems thinking in chemistry education: Theoretical challenges and opportunities. *Journal of Chemical Education, 96*(12), 2752-2763. https:// doi.org/10.1021/acs.jchemed.9b00416

Simonson, S. R. (Ed.). (2019). *POGIL: An introduction to process oriented guided inquiry learning for those who wish to empower learners.* Stylus Publishing LLC.

Talanquer, V. (2019). Some insights into assessing chemical systems thinking. *Journal of Chemical Education, 96*(12), 2918-2925. https://doi.org/10.1021/acs.jchemed.9b00218

York S., Lavi R., Dori Y. J., and Orgill M. (2019). Applications of systems thinking in STEM education. *Journal of Chemical Education, 96*(12), 2742–2751. https://doi.org/10.1021/acs.jchemed.9b00261

York, S., & Orgill, M. (2020). ChEMIST table: A tool for designing or modifying instruction for a systems thinking approach in chemistry education. *Journal of Chemical Education, 97*(8), 2114-2129. https://doi.org/10.1021/acs.jchemed.0c00382

Appendix A
Annotated ChEMIST Table

Table A1 Reprinted (adapted) with permission from York, S., & Orgill, M. (2020). ChEMIST table: A tool for designing or modifying instruction for a systems thinking approach in chemistry education. *Journal of Chemical Education, 97*(8), 2114-2129. https://doi.org/10.1021/acs.jchemed. 0c00382. Copyright 2020 American Chemical Society.

Essential Characteristics	**NO Systems Thinking Skills Required**	**Less Holistic (More Analytical)**		**More Holistic (Less Analytical)**
Recognize a system as a whole, not just as a collection of parts.			"Refer to the maps presented by your instructor (and also posted on Canvas) showing Seattle's regional water distribution system. While Seattle can draw from a variety of sources, what is the most likely watershed source of the water that you collected?"	
Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviors.	"Groundwater typically has a much higher conductivity (300-700 µS/cm) than surface water, because the water absorbs ions as it moves through underground mineral surfaces. Given your conductivity measurement do you think Seattle's water is from a surface or groundwater supply?"	"…how and where was the water cleaned and treated before you sampled it?"		
Identify variables that cause system behaviors, including unique system-level emergent behaviors.			"…alkalinity and hardness analyses have some overlap in what they measure. What is the chemical component that they both measure? In what way are they different?"	

Examine how system behaviors change over time.		"For each of the four analyses you completed (temperature, chlorine, pH, conductivity), do your results match what SPU has previously reported on their drinking water website?"		
Identify interactions between a system and its environment, including the human components of the environment.				

Appendix B
Description of Activity Revisions

Post Lab 1 Reflection

<u>Revision (R in Table 1)</u>

The goal was to lead students to develop a hypothesis explaining why ground water has higher conductivity than surface water. A diagram depicting water accumulation in an aquifer was provided. The diagram modelled part of the water cycle and the diffusion of water through layers of soil. Students were then asked to deduce whether ground water or surface water would have higher conductivity. This question served a foundational purpose for the next added question and required mid-level systems thinking skills. Based on principles of equilibrium and diffusion, students should be equipped with adequate foundational knowledge to develop an appropriate hypothesis and thus demonstrate the ability to "examine the organization of components within a system" and "describe how system level behavior changes over time" (York & Orgill, 2020). Additionally, revisions brought in a new systems thinking skill altogether: "identify the way in which components of a system are connected" (York & Orgill, 2020). Before this edit, skills relating to cyclic nature of systems were not targeted. Therefore, in Table 1, the incorporation of this systems thinking skill is represented as a star.

<u>Insertion (I in Table 1)</u>

The ultimate goal was to prompt students to demonstrate the ability to "use system-level behavior over time trends under one set of conditions to make predictions about system-level behavior over time under another set of conditions" (York & Orgill, 2020). Students were provided conductivity data from City of Madison Public Utilities, which they were told sources water from an aquifer. Then they were asked to compare Madison's data to the data students collected during lab and reason whether Seattle's tap water was sourced from groundwater or surface water. To correctly reason through this, students must have correctly interpreted that the rise in conductivity of ground water over time is due to water interaction with soil. They must then extrapolate that this phenomenon is much reduced for surface water, resulting in lower conductivity. Finally, comparing real conductivity values of water sourced from an aquifer to their own Seattle tap water conductivity measurements, they would be prepared to make an appropriate prediction. From an instructional lens, conductivity was considered "system-level behavior," thus Madison and Seattle can be thought of as distinct sets of conditions.

Deletion

A question that tasked students with drawing a map of the path Seattle municipal water takes from mountain to tap was removed. The information required to answer this question was discussed during the pre-lab lecture, so students were able to construct a map without utilizing holistic systems thinking skills. Thus, it was deemed unnecessary to include after revisions.

Post Lab 2 Reflection

Insertion 1

Students were asked about the relationship between seasons and water availability. Living in Washington, the students should be able to predict this accurately based on their personal experience and observations of the water cycle.

Given a graph depicting the seasonal alkalinity variation (Figure 1), students were asked to describe the alkalinity trend in relation to season, where Quarter 1 data points are taken in March and Quarter 3 data points are taken in September.

Students are informed that the water supplied to Seattle University passes through the Cedar Falls Dam, a porous rock dam, before alkalinity measurements are taken. Students are then asked to hypothesize how the dam would affect the water sample's alkalinity. Having previously investigated an aquifer diagram (described above), students should be able to reasonably predict the dam's effect on the water sample.

To continue investigating the system, students are asked the main source of the water in the SPU measurement besides the water that passes through the dam. By this point, students have been provided with sufficient background information about the water cycle and maps of the local water system to deduce the other surface water sources.

Finally, students are asked to synthesize the information explored in this series of questions into a concise explanation of the observed seasonal variation of alkalinity. Over the course of these guiding questions, students must recognize that during drier months, a larger proportion of water in the SPU water sample has passed through the dam, therefore increasing alkalinity. In the wetter months, the SPU water sample is diluted by surface water sources, decreasing alkalinity measurements. Many systems thinking skills must be demonstrated along the way to arrive at this conclusion, in which students finally "explain the causes of cyclic behaviors within a system" (York & Orgill, 2020).

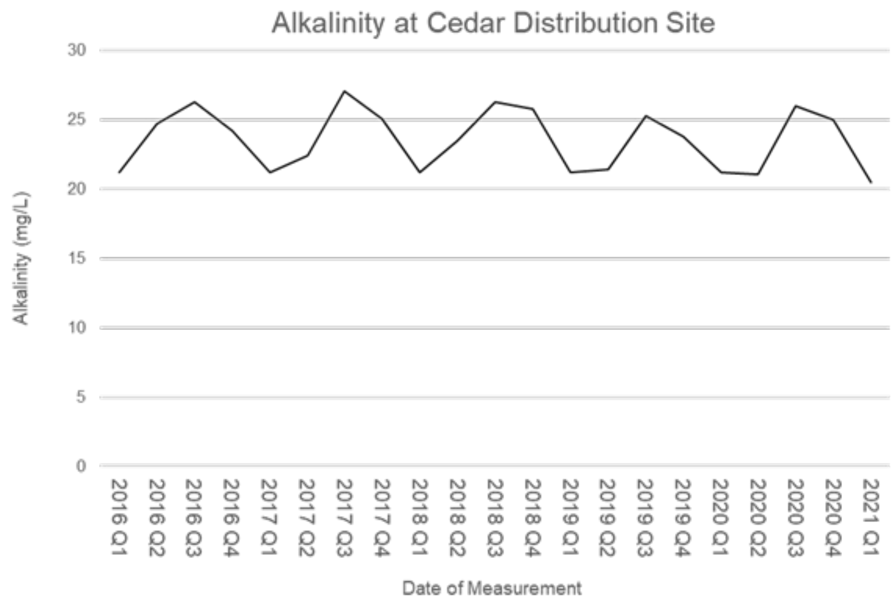

Figure B1 Cyclic variation of alkalinity of water collected at Cedar Distribution cite based on SPU public data (City of Seattle, 2022).

Appendix C
Systems Thinking Exploration

Why?

A system is a group of parts that can have a variety of interactions that contribute to a conducive whole. The topics often explored in introductory chemistry and biology courses are investigated as isolated topics, even though they are influenced by the complex systems in which they occur. This activity investigates "systems thinking," which is a tool for enhancing critical thinking and analyzing systems effectively.

Learning Objectives

- Explore systems thinking
- Begin applying a systems thinking lens to the Drinking Water Lab

Refer students to Figure 2, the Systems Thinking Hierarchical Model pyramid, in Orgill et. al (2019). The figure was edited to label levels A-H from base of pyramid to top.

Figure C1 Systems Thinking Hierarchical Model pyramid (Orgill et al., 2019).

Key Questions

1. What do the different colored regions of the pyramid represent?
2. How do the analysis, synthesis, and implementation regions relate to each other?
3. Looking at the orange region of the pyramid, what skills are described there?
4. Now, look at the skills in the green region. How does the green region differ from the orange?
5. Finally, look at the purple region. Why is it at the top of the pyramid?
6. With the knowledge that systems thinking emphasizes the importance of the upper levels (A, B, C, etc.) of the pyramid, can you deduce the definition of systems thinking?
7. As you explored in Question 2, the systems thinking model is depicted as a pyramid because each level is contingent on the skills below. In an introductory course like general chemistry, what part of the pyramid would you expect to focus on?

8. Why is systems thinking an especially important skill for chemists and biologists?
9. What is an example of a topic from class that required you to understand the cyclic nature of systems?
10. In your experience, what do you need to know about a system to make a prediction about its future behavior?

Refer students to plastic recycling web in Lee & Liew (2021), Figure 1.

Figure C2 Process for plastic recycling (Lee & Liew, 2021).

Information Exercise

For each question below, please give the level letter and description.

1. If you and your friend had drawn this figure, what level (A, B, C, etc.) of the pyramid were you demonstrating?
2. You correctly induce that inhibition at the "extraction and processing" and the "pyrolysis" steps would result in decreased fuel and oil production. What level of thinking skill from the pyramid have you demonstrated?
3. Your friend hypothesizes that increasing the effectiveness of mechanical recycling would increase demand for molding and processing, lessen the demand for virgin polymer, and lessen materials available for tertiary or quaternary recycling. What level of thinking skill from the pyramid have they demonstrated?
4. Upon observation of the system, changes in international tariffs influence consumer application and the extent to which plastic waste is generated or can be reused. On the pyramid, how would you classify tariffs and their influence?

Wrap Up

1. How might systems thinking help you understand the chemistry concepts at play in the water quality lab?

Appendix D
Systems Thinking Exploration Facilitation Guide

Systems Thinking

Systems thinking is the lens that encourages students to not simply engage with parts of the system, but examine complex or emergent behaviors, trends, cyclic natures, and the boundaries of systems. Recognizing the system as an integrated whole is dually a learning outcome and a higher-order thinking skill required for the next generation of engaged scientists. The working definition of systems thinking is provided:

> Systems thinking is a holistic approach for examining complex, real-world systems, in which the focus is not on the individual components of the system but on the dynamic interrelationships between the components and on the patterns and behaviors that emerge from those interrelationships (York et al., 2019, p. 2742).

Science education has previously been dominated by reductionist methods aiming to reduce complex systems into digestible parts (Orgill et al. 2019). Although the reduction of complex problems into small pieces is extremely useful for furthering science and standardized testing, it limits pliability of student thinking. Systems thinking is not designed to replace reductionist methods of teaching and learning, but should instead supplement them (Orgill, et al. 2019). Many challenges facing current day students and scientists—global warming, materials recycling, water sanitation, gene editing—require extensive skills for reasoning within the context of a system.

Systems thinking has been widely acknowledged as the next step for science education because of its ability to enhance students' critical thinking and problem solving while increasing topic engagement. Strengthening systems thinking skills can look like building models, designing concept maps, predicting behavior, or analyzing boundaries of knowledge while incorporating environmental, social, and economic influence (Jegstad & Sinnes, 2015).

Facilitation Notes

Through beta testing, students have been observed to have trouble understanding the purpose of systems thinking and its applicability to the Water Quality Analysis lab. To help facilitate these connections, here are some facilitation tips we recommend:

- Before class, think of an example from your research in which you have used systems thinking skills and share with the class at the beginning of the activity.
- Give a time limit for the activity and inform students you will be having a report-out component.

- During the report-out portion, focus on questions 6 and 8-10, being sure to give the literature definition after the discussion of question 6.

- Feel free to inform students that this is not a novel idea, but it puts language to a learning process they are possibly familiar with.

Systems Thinking Hierarchical Pyramid (Orgill et al., 2019)

This pyramid is a tool for visualizing systems thinking skills and recognizing how they build upon each other. It has been included in the systems thinking activity as the main model for exploration of the topic.

ChEMIST Table (York & Orgill, 2020)

Refer to Figure 2, the Systems Thinking Hierarchical Model pyramid, in Orgill et. al (2019).

Figure D1 Systems Thinking Hierarchical Model pyramid (Orgill et al., 2019).

The following table has been used to evaluate current activities and guide our revisions to the updated Water Quality Analysis lab. The leftmost column describes desired learning outcomes while the other three columns include student behaviors on the spectrum from "more analytical" to "more holistic" that demonstrate the specified learning outcome. The "analytical" column aims to familiarize students with the parts of the system, while the "holistic" column gets students to practice skills critical to systems thinking. Examining this column can help us understand what systems thinking skills look like when applied.

This is an additional resource that neither you nor the students will be using actively during the activity, but it provides a helpful breakdown of the skills critical to systems thinking.

Table D1 Reprinted (adapted) with permission from York, S., & Orgill, M. (2020). ChEMIST table: A tool for designing or modifying instruction for a systems thinking approach in chemistry education. *Journal of Chemical Education, 97*(8), 2114-2129. https://doi.org/10.1021/acs.jchemed.0c00382. Copyright 2020 American Chemical Society.

Refer to the ChEMIST Table in York et al. (2020).