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Applications of Systems Thinking in STEM Education

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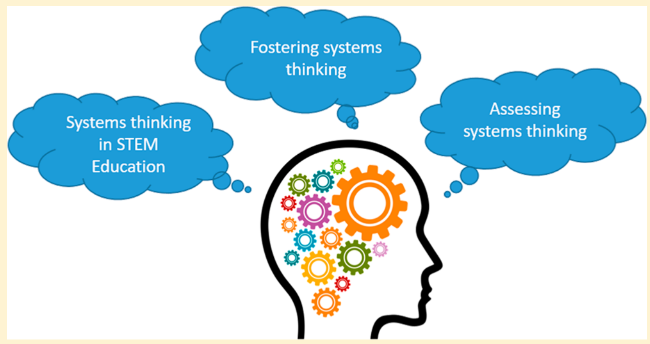
Supporting Information

ABSTRACT: Systems thinking is a holistic approach for examining complex problems and systems that focuses on the interactions among system components and the patterns that emerge from those interactions. Systems thinking can help students develop higher-order thinking skills in order to understand and address complex, interdisciplinary, real-world problems. Because of these potential benefits, there have been recent efforts to support the implementation of systems thinking approaches in chemistry education, including the development of the IUPAC Systems Thinking in Chemistry Education (STICE) Project and this Special Issue of the *Journal of Chemical Education*: "Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry". As part of these efforts, our purposes in this paper are to describe some of the potential benefits associated with systems thinking approaches, to identify the STEM education fields that have employed systems thinking approaches, to summarize some of the major findings about the applications of systems thinking in STEM education, and to present methods that have been used to assess systems thinking skills in STEM education. We found that, in general, systems thinking approaches have been applied in life sciences, earth sciences, and engineering but not in the physical or mathematical sciences. We also found that the primary emphasis of peer-reviewed publications was on the development of students', rather than teachers', systems thinking abilities. Existing tools for the assessment of systems thinking in STEM education can be divided into (a) assessment rubrics, (b) closed-ended tools, and (c) coding schemes, with each type of assessment tool having its own unique advantages and disadvantages. We highlight one particular case in which researchers applied an interdisciplinary framework for comprehensive assessment of systems thinking. Although systems thinking has not been widely researched or applied in chemistry education, many of the conceptual frameworks applied to systems thinking in other STEM education disciplines could potentially be applied in chemistry education. We argue that the benefits observed when applying systems thinking approaches in other STEM education disciplines could facilitate similar results for chemistry education. Finally, we provide considerations for future research and applications of systems thinking in chemistry education.



KEYWORDS: *General Public, Problem Solving/Decision Making, Learning Theories, Systems Thinking*

INTRODUCTION

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.[1−12] While systems thinking approaches were originally employed in fields such as business, biology, physics, and engineering, more recently these approaches have been applied in an educational context.

Proponents of using these approaches have identified multiple potential benefits of using systems thinking in the context of teaching and learning, and many of these benefits are particularly relevant for STEM education. For example, systems thinking is proposed to be closely related to higher-order thinking skills,[13] such as critical thinking.[14,15] Accordingly, approaching STEM content through a systems thinking perspective can increase students' retention of material as well as their problem-solving abilities.[16,17] Instructors who have used systems approaches in their classrooms have reported that students are active participants in their learning,[15−20] learn content more deeply and conceptually,[10,13,14,19,21−25] ask better questions,[15,19] and make more connections between concepts both within and between disciplines.[14−17,19,21,26−29] Overall, systems thinking approaches are student-centered and

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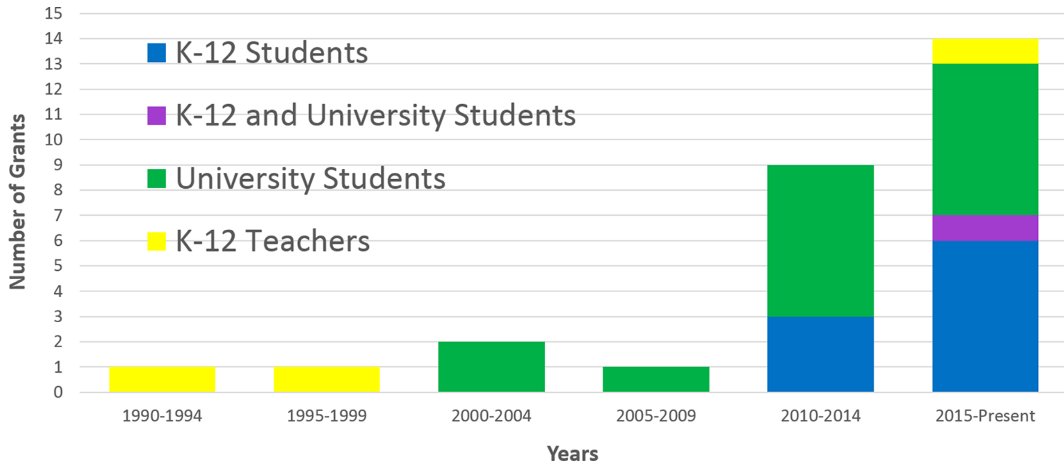

Figure 1. Target groups for NSF-funded grant projects focusing on the use of systems thinking in STEM education.

appear to motivate students to learn and develop the abilities needed to understand and deal with complex, real-world problems.[3,4,8,10,15,19−21,23,29−38] According to Richmond (ref 20, pp 118−119):

> *The systems thinking paradigm, when combined with the learner-directed learning process, will breed students who are hungry to understand how things really work and who will continually be looking for how these workings might change over time as a consequence of shifts in the relative strengths of the underlying dynamic relations.*

From an instructor's perspective, systems thinking can facilitate the development and delivery of interdisciplinary courses and material by providing organization or a unifying framework by which concepts from different disciplines can be connected and, thus, covered in a deeper, more conceptual manner.[14,16,23,28,39,40] Hayden et al. report that implementing a systems thinking approach has also helped instructors improve their teaching practices.[41]

Although systems thinking approaches have mainly been used in the fields of biology, geosciences, and engineering education, there has been a recent call[42] for the use of these methods in chemistry education, which has resulted in the development of the IUPAC Systems Thinking in Chemistry Education (STICE) Project[43] and this Special Issue of the *Journal of Chemical Education.*[44] As members of the STICE Project and in order to provide background to support the future implementation of systems thinking approaches in chemistry education, we focus here on the use of systems thinking approaches in other STEM education fields, as these can inform the future use of systems thinking approaches in chemistry education. We start by identifying the STEM disciplines that have employed systems thinking approaches for teaching and learning and give an overview of some of the major themes and findings about the use of systems thinking approaches in STEM education, including a more detailed discussion of the assessment of systems thinking. We then end with a discussion of gaps in the literature and implications for the use of systems thinking approaches in chemistry education.

■ SYSTEMS THINKING IN STEM EDUCATION

Despite the efforts of individual teachers, schools, and foundations to support and implement systems thinking approaches in schools,[19] systems thinking has not been integrated into STEM education to any great extent, particularly in compulsory education.[28,33,45] Our purpose in this section is to identify the STEM fields in which systems thinking approaches have been previously employed in the context of teaching and learning, as well as to provide an overview of some of the major themes and findings in the limited published reports of the use of systems thinking in STEM education. We chose to look at (1) funded grant projects focused on systems thinking in STEM education and (2) published reports of the use of systems thinking in STEM education in order to develop an understanding of some of the trends associated with the implementation of systems thinking approaches in STEM education.

Funded Grant Projects in STEM Education

We limited our search to grant projects that had been funded by the U.S. National Science Foundation (NSF). The NSF has an easily accessible, searchable database of funded projects that made it a convenient source for our data. We recognize that the absolute numbers of funded projects and funding devoted to the use of systems thinking in STEM education will differ from country to country, but we suspect that the trends we identified in our search of the NSF database will be similar in other countries, on the basis of our review of publications focused on the use of systems thinking in STEM education (discussed in the section that follows).

In the NSF database, we searched for grant projects in which systems thinking was used in STEM education in a significant way. We searched both current and expired grant projects for the presence of *systems thinking* in either the title or the abstract. We reviewed abstracts and eliminated projects for which systems thinking was not a major component for teaching STEM topics and subjects. We categorized each of the remaining grant projects according to target group (K−12 students, university students, teachers, etc.) and content area (biology, engineering, etc.).

At the time of our review (late 2018), the NSF had awarded approximately $25.8 million in funding for a total of 27 STEM education grant projects in which systems thinking played a major role (Figure 1). The majority of these projects were funded in the current decade, suggesting an increased interest in the use of systems thinking approaches in STEM education in recent years. The first NSF-funded project focused on the use of systems thinking in STEM education was Project Cross-Curricular Systems Thinking and Dynamics Using STELLA (CC-STADUS).[15] It was funded in 1993 and focused on

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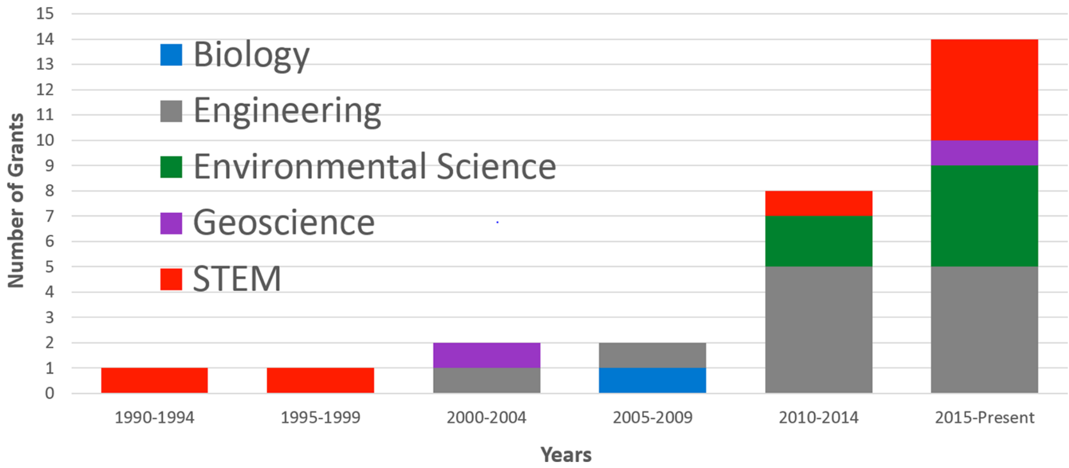

Figure 2. Major content areas of NSF-funded grant projects focusing on the use of systems thinking in STEM education. Note that "STEM" refers to projects that focused on the use of systems thinking in all STEM disciplines, as opposed to projects that focused on the use of systems thinking in a single discipline.

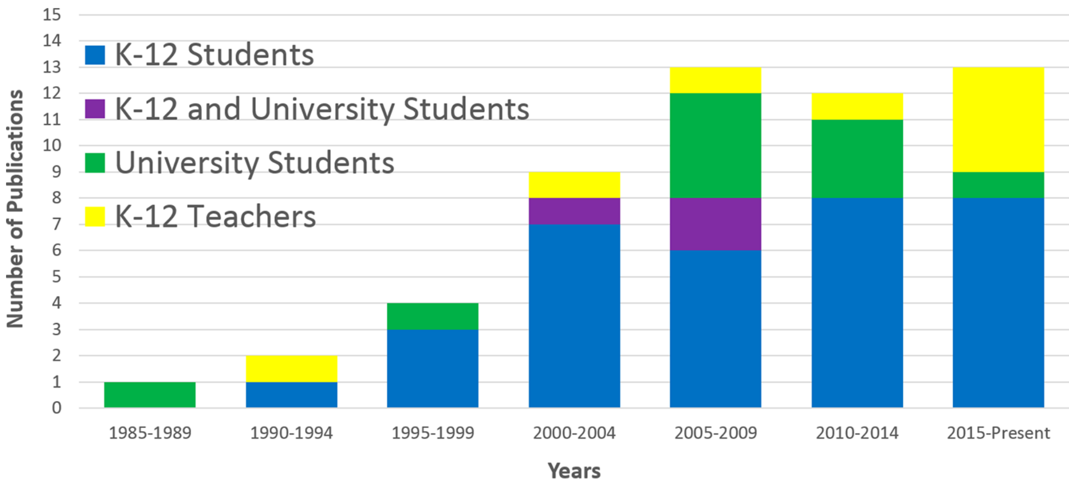

Figure 3. Target groups for peer-reviewed publications focusing on the use of systems thinking in STEM education.

building K−12 teachers' abilities to employ systems thinking approaches in their classrooms. Over time, the focuses of the grant projects have shifted mainly toward helping students develop systems thinking skills (Figure 1). To date, no projects have focused on providing university instructors with professional development about the use of systems thinking approaches.

Even though, in theory, systems thinking approaches should be applicable in all STEM fields, NSF funding for the application of systems thinking approaches to STEM education is limited in the disciplines represented. Most of the funded projects are in the areas of engineering or environmental sciences, with a few projects being funded in other natural science disciplines (Figure 2). No awards have been made to look exclusively at systems thinking approaches in mathematics, technology, or any of the physical sciences.

Peer-Reviewed Publications in STEM Education

We searched the Education Resources Information Center (ERIC) database for publications that included the keywords *systems thinking* in the title or abstract. We also searched Google Scholar for the term *systems thinking* combined, individually, and with the name of each of the STEM disciplines. We read the corresponding abstracts in order to select those publications that focused on the use of systems thinking in education. We then identified those that included STEM education as a focus (instead of, for example, being an article about systems thinking in general or about systems thinking in a non-STEM discipline). We further limited our pool to peer-reviewed publications: journal articles, dissertations and theses, and book chapters. Because the field of systems thinking in STEM education is relatively new, our pool includes research articles and practitioner articles as well as some theoretical pieces. We categorized each of these publications according to target group and content area, as we did for the NSF-funded grant projects. Ultimately, we categorized 54 publications (refs10, 13, 15, 18, 22, 24−27, 34, 38, 41, and 46−87).

The majority of the publications we reviewed focus on the use of systems thinking in K−12 STEM education, as opposed to tertiary STEM education (Figure 3). Additionally, the majority of publications focus on facilitating student learning through systems thinking principles. Fewer studies focus on instructors' understandings and use of systems thinking in STEM education.

As with the funded grant projects, we found that certain disciplines tend to be represented more than others when it comes to integrating systems thinking into STEM education

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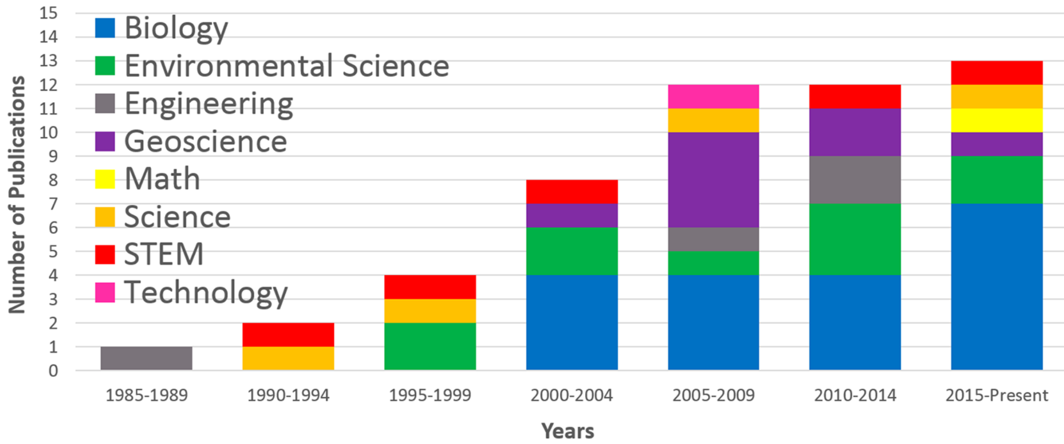

Figure 4. Content areas of peer-reviewed publications focusing on the use of systems thinking in STEM education. Note that "STEM" refers to projects that focused on the use of systems thinking in all STEM disciplines, as opposed to projects that focused on the use of systems thinking in a single discipline. "Science" refers to a focus on multiple science fields without a focus on engineering or mathematics.

(Figure 4). In the case of peer-reviewed publications, biology, environmental science, geoscience, and engineering were represented more than other fields. This finding is consistent with the results of a recent review of the literature about the teaching and learning of complex systems.[25] Additionally, we found, as did those authors, that many of the research articles we read were somewhat exploratory in nature, suggesting that the use of systems thinking in STEM education is not completely established as an area of research.

The fact that certain disciplines are more represented in the literature on systems thinking in STEM education may be related to the natures of the disciplines themselves. For example, biology focuses on a number of different "systems" and geoscience-related fields (including Earth science) focus on a number of different "cycles." One of the fields of engineering is *systems engineering*. It may be that these fields lend themselves more naturally to a systems approach or that they are already using some variation of a systems approach. For example, experts in geology education examined systems thinking skills of geology majors as compared with those of students from other disciplines.[50] They found that undergraduate geology students demonstrated more dynamic and cyclic thinking than students in other fields when presented with a systems task.

Alternately, certain disciplines may be represented more than others in the publications we reviewed because systems thinking has champions in those disciplines. For example, Assaraf and Orion have published several articles in the areas of systems thinking in Earth- and geoscience.[46−48,50] The group of Verhoeff, Boersma, and Waarlo have published multiple articles in the area of systems thinking in biology;[24,51,81−84] and Hmelo-Silver has partnered with multiple researchers to publish in the areas of systems thinking in biology and systems thinking in environmental science.[22,39,58−60,64] Without these and a few other "champions", there would be little research in the area of systems thinking in STEM education.

Finally, we note that a lack of publications in a particular discipline does not mean that systems thinking has not been applied in the context of teaching and learning in that discipline. The analysis presented here provides a *relative* idea of where systems thinking efforts are currently focused.

Summary of Major Findings Related to Systems Thinking in STEM Education Publications

The primary focus of the peer-reviewed publications reviewed in the previous section is on students' development of systems thinking skills. A small number of publications focused on teachers' use and implementation of systems thinking approaches. In this section, we summarize the major findings related to these two topics. Where the findings in STEM education are supported by studies about the application of systems thinking in other fields, we include those references, as well.

Students' Development of Systems Thinking Skills. It has been suggested that an understanding of complex systems is part of scientific literacy.[23,80] If systems thinking is a tool for understanding complex systems, it is important to develop systems thinking skills in STEM students. Unfortunately, systems thinking is not a "natural" way for humans to think and may even be counterintuitive.[8,22,64] Students tend to think of systems in terms of isolated, static components.[69] Additionally, they do not take into account spatial or temporal scales when considering a complex phenomenon. Booth Sweeney and Sterman, working with graduate students in management, found that even educated adults have very limited systems thinking skills.[3]

Fortunately, research suggests that systems thinking skills can be developed through carefully designed instruction.[13,22,27,46,47,71,84,88] Although it is generally assumed that systems thinking skills are easier to develop in older students, even young children have been shown to have the ability to develop some systems thinking skills with appropriately designed instruction.[4,46,63,86]

Consistently, research indicates that systems thinking skills must be explicitly taught if they are to be learned. It is not enough for students to participate in a well-designed systems thinking activity, although active participation in such an activity is necessary for the development of systems thinking skills.[46,83] Students need explicit, scaffolded guidance in order to develop systems thinking skills and to think about the relationships between the different levels within a system.[24,32,61,63,80,84]

Just as students will not develop systems thinking skills by participating in unguided systems thinking activities, they will, likewise, not develop systems skills by learning about systems

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Table 1. Systems Thinking Assessment Tools in STEM Education Published from 2000 to 2019

Assessment-Tool Type, Advantages, and Disadvantages	Type of Data Being Assessed	Refs[a] (*N* = 16)
Assessment rubric: widest scope of assessment but requires the most resources to develop	Concept map	Brandstädter et al. (2012),[45] Mehren et al. (2018),[93] Stewart (2012),[94] Tripto et al. (2013)[95]
	Conceptual model	Hung (2008),[96] Lavi and Dori (2019)[92]
	Text: written responses	Grohs et al. 2018[97]
Closed-ended: most easily scalable but also most limited in scope of assessment	Text: terms inputted in box diagram	Sibley et al. 2007[77]
	Multiple-choice questionnaire (topic-specific)	Assaraf and Orion (2005, 2010),[46,48] Batzri et al. (2015),[50] Mehren et al. (2018)[93]
	Multiple-choice questionnaire (self-reported)	Gero and Zach (2014)[55]
Coding scheme: requires the least amount of resources to develop but also the least reliable and least scalable	Text: interview transcripts	Assaraf and Orion (2010),[48] Hmelo-Silver et al. (2007)[59]
	Text: written responses	Eilam (2012),[52] Hiller Connell et al. (2012),[57] Mehren et al. (2018),[93] Yoon (2008)[87]

[a]Some of the studies cited included more than one type of assessment tool.

or by learning about systems thinking concepts.[13] They must learn about systems thinking *while* applying systems thinking to a particular context.[52]

Even if students participate actively in well-designed activities which are accompanied by explicit, scaffolded guidance, they will not all develop the same level of systems thinking skills. Research indicates that students' abilities to develop systems thinking skills depend on their cognitive abilities and their temporal and spatial thinking abilities.[46,52] Development of systems thinking skills may also be linked to students' content knowledge, as content knowledge provides both the context for systems thinking, as well as the motivation for developing systems thinking skills.[24,50,68]

Teachers' Use and Implementation of Systems Thinking Approaches. Researchers have specifically noted the limited amount of studies focused on teachers and instructors and systems thinking.[73,74,76,78] Three of the four publications we found that focus exclusively on teachers' understandings and implementation of systems thinking approaches came from the same study, only reporting different findings in each publication. Overall, these limited studies suggest that to effectively facilitate student learning through a systems thinking approach, teachers must participate in scaffolded, guided systems thinking activities as students,[73,76] receive didactic instruction about how to teach systems thinking concepts to their students,[74] and have access to continual support while implementing these methods in the classroom.[79]

ASSESSMENT OF SYSTEMS THINKING IN STEM EDUCATION

Because the assessment of systems thinking informs and contributes to its facilitation, we shall now discuss the topic of systems thinking assessment in STEM education. The present section consists of three parts: (1) a brief survey of the literature about systems thinking assessment in STEM education, (2) a description of an interdisciplinary rubric developed specifically for assessment of systems thinking in STEM education, and (3) a discussion of considerations for the assessment of systems thinking in chemistry education.

Survey of Systems Thinking Assessment in STEM Education

In an educational context, systems thinking is the skill of comprehending systems as well as describing questions, circumstances, or problems from a systems perspective.[46,89−91] Existing tools for the assessment of systems thinking in STEM education can be divided into three types: assessment rubrics consisting of classification and scoring guidelines, closed-ended tools such as multiple-choice questionnaires, and coding schemes for written responses and interviews. Each type of assessment tool has its own unique advantages and disadvantages. Table 1 lists some of the tools used for comprehensive assessment of systems thinking in STEM education published from 2000 to 2019 in peer-reviewed journals. Figure 5 shows the STEM education fields in which these tools were developed. Most of the tools were developed to assess students' systems thinking abilities, whether at school or in higher education. Two of the tools were specifically developed to examine teachers'[92] or experts'[59] systems thinking skills.

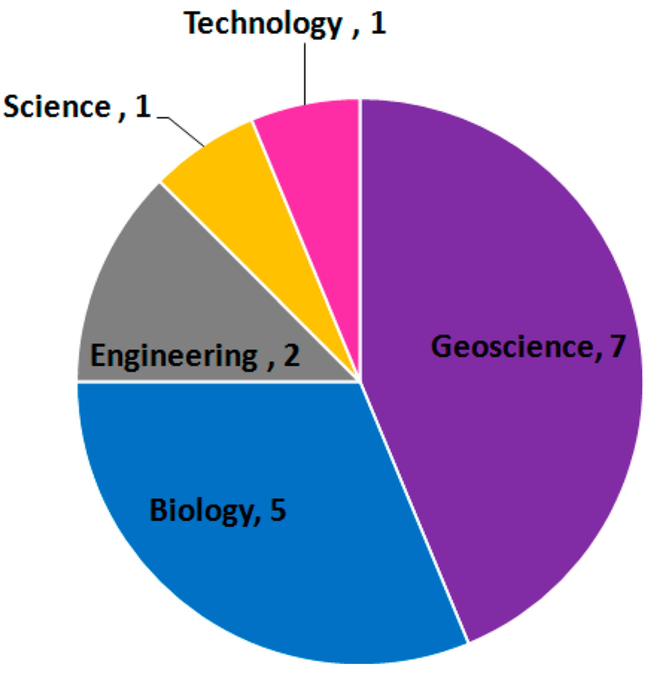

Figure 5. STEM education fields that have published systems thinking assessment tools. The numbers in the chart represent publications that have included systems thinking assessments.

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Saxton et al. stated that a common measurement system is required for STEM education in order to improve students' systems thinking.[98] Their statement was echoed by the Next Generation Science Standards (NGSS), which include *systems* and *system models* as crosscutting concepts in science education.[99] In our examination of the STEM education literature, we found five cases in which researchers applied an interdisciplinary framework for comprehensive assessment of systems thinking. Hmelo-Silver et al. applied Structure-Behavior-Function (SBF) theory to explain the differences between expert and novice understanding of natural (human respiratory system) and artificial (aquarium) biological systems.[59] Originating in computer science, SBF theory accounts for a system's constituent parts, their purposes within the system, and how their functions are enabled within the system. Yoon applied the Complex Systems Mental Models framework to improve student knowledge of genetic engineering.[87] This framework categorizes different beliefs about a complex system, from a "clockwork" (simple) model to a complex one. Stewart applied the Structure of the Observed Learning Outcome (SOLO) taxonomy to measure the differences in complexity of learning outcomes between students who participated in a concept mapping activity and those who did not.[94] The SOLO taxonomy provides a classification of the structural complexity of students' written responses. Grohs et al. developed an interdisciplinary framework in engineering education and social sciences and applied it to the assessment of systems thinking expressed in students' written responses to a problem scenario.[97] Lastly, Lavi and Dori developed an interdisciplinary framework common to science and engineering education and applied it to the assessment of systems thinking expressed in conceptual models constructed by teams of science and engineering teachers.[92]

Systems Thinking Assessment Rubric for Science and Engineering Education

Lavi and Dori[92] created their framework on the basis of the three system aspects view (function, structure, and behavior), which is widely accepted in systems engineering.[90] Following a comprehensive literature review of systems thinking assessment in science and engineering education, they formulated a list of common attributes of systems thinking and allocated each one into one of the three system aspects. This conceptual framework or classification for systems thinking assessment is the only one based on multiple STEM education sources and developed specifically for transdisciplinary assessment of systems thinking, in line with the need for common measurement identified by Saxton et al.[98]

Table 2 shows the classification of system aspects and attributes of systems thinking common to science and engineering education, as formulated by Lavi and Dori, with a short description of each attribute.[92] The benefit of such classification is that it allows for the development of assessment tools for systems thinking skills specific to science and engineering education. As Table 2 shows, the classification contains three system aspects—function, structure, and behavior—with each one further divided into a number of systems thinking attributes. Note that the first attribute on the list, outcome or intended purpose, differs between science and engineering: whereas outcome is relevant to science and natural phenomena, intended purpose is relevant to engineering and artificial systems.[46,50,100] The next subsection, Systems Thinking Assessment in Chemistry Education, contains Table 3, which shows a specific example of this classification in chemistry education. Table S1 in the Supporting Information shows select terms from the literature that were used in creating this classification.

Table 2. Systems Thinking Attributes and Descriptions[a]

System Aspect and Systems Thinking Attributes	Systems Thinking Attribute Description: What Students Should Be Able To Identify
	System Function
Outcome or intended purpose (in relation to the system's stakeholders)	Natural system: expected outcome Artificial system: intended purpose
Complexity levels	Hierarchy of system functions and their subfunctions
Main function	Main activity of the system Objects affected by the main activity Enablers of the main activity
System boundary	Entities that are affected by the system and entities that affect the system but are not significantly affected by the system
	System Structure
Main object and its parts and attributes	Object affected by the system's main activity That object's parts, features, and subtypes
Structural relations	Static relations between objects of the system: whole−part, exhibitor−feature, and type−subtype
	System Behavior
Procedural relations	Dynamic and cause-and-effect relations between system objects and activities: consumption, creation, change (affect), or enablement
Procedural sequence	Sequences of activities: linear, divergent, convergent, or iterative (looping)
Temporary objects and decision nodes	Objects created and consumed within an activity Decisions made by the system or the system's user

[a]Based on the classification formulated by Lavi and Dori.[92]

Lavi and Dori also developed scoring guidelines for the classification shown in Table 2, thereby creating an assessment rubric. They provided raters with detailed instructions for scoring each attribute of systems thinking on a scale from 0 (no expression of that attribute) to 3 (full expression of that attribute).[92] The rubric thus allows for a comparison of the systems thinking abilities of students (or teachers) as they relate to (a) individual attributes or aspects of a given system, (b) a system as a whole, or (c) different types of systems. Although these guidelines were developed for assessing conceptual models constructed using a specific formal methodology, the classification shown in Table 2 could potentially be adapted for use with other types of data, such as written responses to a case study. The scoring guidelines could also be simplified and made qualitative, with a "yes" or "no" assessment of each attribute.

Systems Thinking Assessment in Chemistry Education

Systems thinking has not been widely researched in chemistry education; accordingly, a tool for a comprehensive assessment of systems thinking in chemistry education has not been published. However, the same conceptual frameworks that were applied for systems thinking assessments in other fields of STEM education (see Table 1) could potentially also be applied in chemistry education. For example, the assessment rubric developed by Lavi and Dori could potentially also be applied to chemical phenomena and chemical systems, as the function-structure-behavior view can also apply to chemistry.[92] Table 3 shows a succinct example of how the classification created by Lavi and Dori could be applied in a qualitative (yes−no) manner to the phenomenon of ocean acidification.

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Table 3. Systems Thinking Attribute Descriptions for Ocean Acidification[a]

System Aspect and Systems Thinking Attributes	Hypothetical Examples of Student Descriptions in Relation to Each Attribute of Systems Thinking
	System Function
Outcome[b]	Substantial decrease in food sources of fish eaten by humans
Complexity levels	Ocean acidification can be split into (1) ocean temperature increasing, which affects both the atmosphere and marine life; (2) CO_2 dissolving, which affects both the ocean and the atmosphere; and (3) decrease in $CaCO_3$, which affects marine life.
Main function	Main activity: ocean water absorbing CO_2 from the atmosphere
	Objects affected: ocean water and CO_2
	Enablers: atmosphere
System boundary	Human activity affects the system by releasing CO_2 into the Earth's atmosphere, but this activity is not affected by the system.
	System Structure
Main object and its parts and attributes	The main object is the ocean: it consists of surface, depth, and marine life, and its affected attribute is pH level.
Structural relations	Whole−part: ocean consists of surface, depth, and marine life
	Exhibitor−attribute: ocean exhibits pH level
	Type−subtype: different types of marine organisms (shell-carrying organisms and coral)
	System Behavior
Procedural relations	Enablers: atmosphere
	Objects affected: CO_2
Procedural sequence	Linear sequence in six steps:
	1. CO_2 is absorbed by the ocean surface.
	2. Quantity of H^+ in ocean water increases.
	3. Quantity of CO_3^{2-} in ocean water decreases.
	4. Building and maintaining $CaCO_3$ structures becomes more difficult.
	5. Quantity of shell-carrying and coral marine life decreases.
	6. Quantity of predators of shell-carrying and coral marine life decreases.
Temporary objects and decision nodes	CO_2 is constantly being created and exchanged among the ocean surface, ocean depth, and atmosphere, never remaining in the same amount.

[a]Information taken from ref 101. [b]Ocean acidification is a natural phenomenon and as such has outcomes and no intended purpose.

Although assessment tools are usually used to examine student understandings and abilities, a tool for assessment of systems thinking in chemistry education could serve additional purposes. It could potentially be used as part of chemistry teacher training or integrated into chemistry learning materials for summative and formative assessment purposes. Such a tool could also be used by researchers who are examining factors that influence the development of students' systems thinking skills in chemistry education.

■ POTENTIAL IMPLICATIONS FOR INTEGRATING SYSTEMS THINKING INTO CHEMISTRY EDUCATION

Other STEM education fields have established a base on which efforts directed at integrating systems thinking approaches into chemistry education can be built. However, there are some gaps in the literature that should be considered before employing systems thinking in a chemistry education context. We highlight some of these here:

- A majority of the studies about the use of systems thinking in education have taken place in the context of the life sciences, geosciences, and engineering. Relatively few studies have taken place in the physical sciences.[25,49] How might the use of systems thinking be informed by previous efforts? How might the implementation of systems thinking in chemistry or other physical sciences differ from those in, for example, life sciences? Which systems thinking skills are particularly relevant in chemistry teaching and learning? What specific challenges might students face when attempting to use systems thinking approaches in chemistry classrooms? What materials and tools are needed to support students' systems thinking in chemistry classrooms?
- Systems thinking is not the only approach for teaching and learning. Nor would it be appropriate for all teaching and learning in a general chemistry course.[9,27] For which chemistry topics is systems thinking particularly well-suited? For which topics is a more reductionist perspective more appropriate? Which currently used teaching strategies, such as context-based learning[102,103] or problem-based learning,[104] could be used or modified to support systems thinking in chemistry education?
- Many of the existing studies about the use of systems thinking in STEM education have been qualitative in nature and have not compared systems thinking methods or understandings with those of a control group.[25] In which specific ways do chemistry students benefit from the use of systems thinking approaches, and how do those benefits differ from those when students are taught with other research-based approaches? Do those benefits differ by student groups (English Language Learners, learners from different ethnic or racial groups, etc.)?
- Assessment is important in guiding both curriculum development and student learning. Which systems thinking skills should be assessed in chemistry education? Which types of systems thinking assessment tools should be used in chemistry education, and how should the choice of tools vary on the basis of the context? For example, which tools should be used for large-scale assessments of general chemistry classes, and

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which should be used for assessing products of chemistry graduate research?

- In order for systems thinking approaches to be implemented in chemistry education, instructors will need professional development about systems thinking concepts and about how to facilitate systems thinking approaches efficiently and practically in their classrooms.[19,26,31,39,79,105] However, very little research has been done about teachers' understandings and use of systems thinking approaches, and none of this work has been carried out with instructors at the tertiary level or specifically with chemistry instructors. What types of professional development are needed to support chemistry educators in their efforts to implement systems thinking approaches?

Although there remains work to be done, we believe that the benefits and results seen from the use of systems thinking approaches in other STEM education fields show great promise for the use of these approaches in chemistry education in the future, and we encourage both chemistry educators and chemistry education researchers to consider the ways in which systems thinking approaches can be best implemented and assessed in chemistry courses. We believe that the summaries and conclusions we have provided in this paper, as well as those of other papers published in this Special Issue of the *Journal*,[1,106,107] will help in this important endeavor.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00261.

Select terms from the literature that were used to develop the list of systems thinking aspects and attributes shown in Table 3 (PDF)

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Notes

The authors declare no competing financial interest.

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