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ChEMIST Table: A Tool for Designing or Modifying Instruction for a Systems Thinking Approach in Chemistry Education

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ChEMIST Table: A Tool for Designing or Modifying Instruction for a Systems Thinking Approach in Chemistry Education

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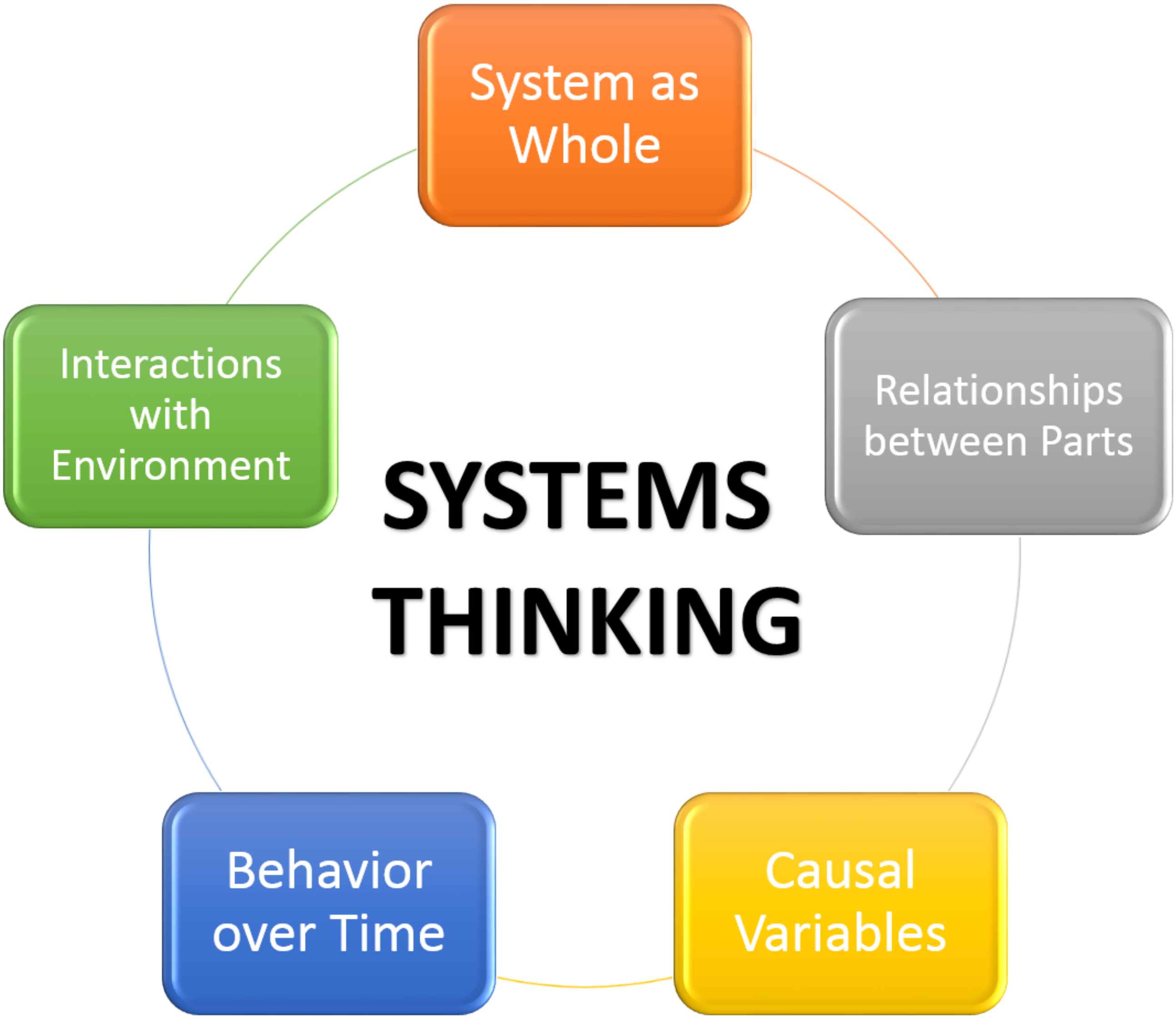
ABSTRACT

Recently, there have been calls to integrate a systems thinking approach into chemistry education in order to strengthen students' conceptual understanding, build their problem-solving capabilities, and prepare them to make informed, ethical decisions about globally-relevant issues, such as sustainability. Unfortunately, implementation of systems thinking approaches in chemistry classrooms currently poses challenges. Exemplar systems thinking materials with a STEM focus are limited, particularly at the tertiary level. Moreover, the science education community has yet to agree upon a systems thinking definition or develop a comprehensive list of systems thinking skills that students should develop. Thus, a current priority for the advancement of systems thinking in chemistry education is the development of resources for instructors and students alike. In the current project, we constructed a tool that provides an operational definition for systems thinking in chemistry education and serves as guide for the design, analysis, and optimization of systems thinking activities. The **Ch**aracteristics **E**ssential for designing or **M**odifying **I**nstruction for a **S**ystems **T**hinking approach (ChEMIST) table identifies five essential characteristics of a systems thinking approach, along with corresponding systems thinking skills through which students can demonstrate their engagement in each essential characteristic. Here, we describe the inspiration and development of the tool. We also provide examples of how the tool might be used to support chemistry teaching and learning from a systems thinking approach. Finally, we present some initial ideas about the relationship between systems thinking and other approaches to chemistry education reform.

GRAPHICAL ABSTRACT



KEYWORDS

First-Year Undergraduate/General; Second-Year Undergraduate; Upper-Division Undergraduate; Chemical Education Research; History/Philosophy; Problem-Solving/Decision Making; Learning Theories; Student-Centered Learning

INTRODUCTION

Previous research in disciplines outside of chemistry has established the benefits of including systems thinking perspectives and approaches in science/STEM education. For example, systems thinking approaches have been shown to increase students' critical thinking and problem solving abilities. They have also been shown to support meaningful learning in that they help students make both intra- and interdisciplinary connections between concepts.[1-2] Many science educators also suggest that the skills associated with systems thinking are a part of science literacy[3-4] and that the development of these skills can prepare students to understand and address complex, real-world problems.[1-3,5-24]

Given these potential benefits, there have been recent calls to integrate systems thinking approaches into chemistry education. In fact, a recent special issue of the *Journal of Chemical Education* (December 2019) focused on "Reimagining chemistry education: Systems thinking, and green and sustainable chemistry."[25] The practical implementation of systems thinking approaches into chemistry classrooms, however, remains challenging at the current time. First, although the *Journal* special issue included and has inspired the development of systems thinking activities for chemistry education,[25-27] examples of systems thinking activities in STEM education are limited, particularly in the discipline of chemistry[1-2,28-30] and at the tertiary level of schooling.[2] Second, there also do not appear to be clear sets of guidelines about how to develop systems thinking activities from scratch or how to modify existing activities to make them more systems thinking oriented.[31] Third, and perhaps most importantly, there is no consensus in either the science or science education communities about what exactly systems thinking is or about the skills in which systems thinkers should engage.[1-2,7,23,32-38]

The Need for an Operational Definition of Systems Thinking in Chemistry Education

Without an operational definition or consensus for what systems thinking is in the context of chemistry education, it is entirely possible—and maybe even likely—that the term could come to mean so many different things to so many different people that it essentially means nothing. This has been seen with the term "inquiry" in STEM laboratory teaching and learning.[39-40] Buck, Bretz, and Towns[39] reported that the lack of a consensus definition for "inquiry" resulted in practitioners and researchers defining and implementing inquiry-based methods in inconsistent and highly individualized ways.

The development of an operational definition for "systems thinking" is not only important for maintaining consistency in the implementation of systems thinking approaches across different chemistry education contexts, but for supporting learners engaged in systems thinking activities. Research from STEM education suggests that systems thinking is not a "natural" way for humans to think.[14,41-42] For example, students do not tend to think of systems as consisting of dynamic, interconnected components (a systems thinking approach). Instead, they think of systems in terms of collections of isolated, static components.[43] Fortunately, research also suggests that systems thinking abilities can be developed through carefully designed instruction in which students are guided to focus and reflect on specific systems thinking skills.[4,8,32,38,41,44-52] In essence, developing systems thinking is challenging and must be done actively and intentionally. Intentionality, however, requires that both instructors and students have an operational definition for systems thinking. Given the breadth of fields in which systems thinking is applied, we argue that the most useful operational definition for our community will not be generally applicable, but will be one that is contextualized in the field for which it is intended: chemistry education.

Intent of the Current Project

Flynn et al.[31] identified several priorities that need to be addressed in order to advance the use of systems thinking in chemistry education. One of those priorities was the development of systems thinking resources for chemistry educators and students. This was our goal with the current project. Specifically, our intention was to develop an initial version of a tool that (1) provides an operational definition of systems thinking for the specific context of chemistry education and (2) can be used as a guide for the analysis, construction, and adaptation of systems thinking instruction for chemistry teaching and learning.

We identified three broad principles to guide the development of the tool:

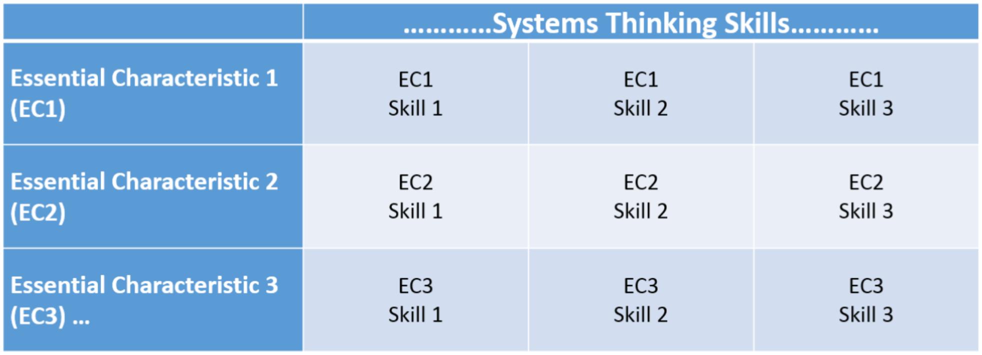
- *The operational definition of systems thinking in chemistry education should be consistent with other published definitions of systems thinking.* While the operational definition might emphasize particular aspects of systems thinking that align with and specifically support chemistry education, the operational definition should not contradict what has already been published about systems thinking. Accordingly, our first step in constructing the tool was to review existing literature about systems thinking in various disciplines and, more specifically, research about systems thinking teaching and learning.
- *The operational definition should include the essential characteristics of systems thinking.* Throughout the various published definitions of systems thinking, there are several common characteristics. Our goal in constructing the tool was to identify a set of essential characteristics that could, in combination, be used to (1) define systems thinking in the context of chemistry education and (2) distinguish systems thinking from other approaches that could potentially be used in chemistry education, while still allowing for flexibility in classroom implementation.
- *The operational definition should address the specific needs of the chemistry education community*. There are certainly many different ways to identify and define the needs of the chemistry education community and its individual stakeholder groups. For the purposes of the construction of the current tool, we were guided by Talanquer,[53] who identified three key features of chemical systems thinking: (1) students should be able to use mechanistic reasoning to explain chemical phenomena; (2) students should learn chemistry content in context; and (3) students should be able to use their chemical knowledge to make decisions and take actions that support the sustainability of the planet.[18-19]

Guiding Literature

Other approaches to science education have been plagued by a lack of a clear definition. One of these, as previously mentioned, is “inquiry.”[39] In an attempt to provide guidance for practitioners, the National Research Council (NRC) identified five “essential features of classroom inquiry.”[54] The features were “essential,” in that, if each of the features was not present, an activity would not be considered full inquiry. For each essential feature, variations of how that essential feature could be implemented in the classroom were provided along a continuum from more student-directed to more teacher-directed. These variations allow a teacher to adjust an activity to the needs of their classroom and students while maintaining the inquiry nature of the activity. Unfortunately, although the NRC definition provided a framework for judging the inquiry-oriented character of classroom and laboratory activities, the definition never gained sufficient traction to become widely accepted, and teachers continued to define “inquiry” as they saw fit.[39]

Another example of an approach to science education that was initially implemented in various ways is course-based undergraduate research experiences (CUREs). At first, there were multiple types of and “definitions” for a CURE; however, in attempt to provide guidance that could be used to establish consistency in CURE approaches, a National Science Foundation panel associated with the Course-based Undergraduate Research Experiences Network (CUREnet) identified five essential/critical characteristics of a CURE. According to the panel, a CURE was defined by the presence of these five characteristics *in the same activity* (although the complete activity could occur over the course of multiple class/lab periods).[55]

Our efforts in creating a tool that could be used to provide guidance and consistency for the implementation of a systems thinking approach in chemistry education were guided by those described above. In essence, we had two goals. The first was to identify a limited set of essential characteristics that, in concert, could be used to categorize an activity as being consistent with a systems thinking approach in chemistry education. Our second goal was related to several published lists of cognitive skills associated with systems thinking.[1] After identifying the essential characteristics, we hoped to correlate each of those characteristics with specific systems thinking skills and to organize the skills associated with each specific essential feature along a continuum, similar to the variations of the essential features of inquiry provided by the National Research Council.[54] Thus, the constructed tool would be presented in the form of a table and would include not only the defining/essential characteristics of a systems thinking approach in chemistry education, but also guidance about the types of skills students would engage in when addressing each of those essential characteristics (Figure 1).



	…………Systems Thinking Skills…………		
Essential Characteristic 1 (EC1)	EC1 Skill 1	EC1 Skill 2	EC1 Skill 3
Essential Characteristic 2 (EC2)	EC2 Skill 1	EC2 Skill 2	EC2 Skill 3
Essential Characteristic 3 (EC3) …	EC3 Skill 1	EC3 Skill 2	EC3 Skill 3

Figure 1. Initial framework for the creation of a tool to guide systems thinking approaches in chemistry education.

Having established the framework presented in Figure 1 for the creation of a tool, our next step was to determine the best way to organize the skills that would be associated with a given essential characteristic of systems thinking. The table of essential features of inquiry provided by the National Research Council (ref *54*, p. 30) organizes variations of each essential feature along a continuum from greater amount of student direction to greater amount of teacher direction. While we considered a similar continuum for the current tool, we ultimately determined that a different continuum was better aligned with systems thinking, the types of skills and abilities involved in systems thinking, and the goals for integrating systems thinking into a chemistry education context: the analytical/elaborative – holistic continuum. As it may be unfamiliar to readers, we describe it in the section that follows.

The Analytical/Elaborative – Holistic Continuum. Hitchins,[56] a researcher in the area of systems engineering, states that developing an understanding of a system requires both an understanding of the parts that compose the system and an understanding of a system as a whole. Thus, we could argue that, from a cognitive perspective, systems thinking involves both analytical skills—which focus on parts—and holistic skills—which focus on wholes. It is important to note that a focus on parts from a systems thinking perspective is distinct from that used in a reductive perspective. In fact, Hitchins uses the term "elaboration" to describe the way that a systems thinker focuses on parts (ref *56*, p. 93):

> Disaggregating or decomposing is the process of breaking up complex systems into smaller, simpler parts. It is the tool of Cartesian reduction, with all its inherent limitations, and as such is inappropriate to systems ideas and methods. Nonetheless, it is often necessary to examine and analyze systems in some detail. The process of "looking inside" a system is elaboration. Unlike decomposition, elaboration does not disconnect parts, but acts rather like a magnifying glass, enabling the user to see and express more detail while that detail remains in situ; connected, dynamic, and interactive.

The concept of placing cognitive processes on a continuum from more analytical/elaborative to more holistic is not new. This continuum has roots in systems engineering, educational psychology, and cultural psychology.[56-58] Although the continuum has been described using various terminologies (i.e., left-brained/right-brained; sequential/global; field-independent/field-dependent, etc.), we find the "analytical/elaborative" and "holistic" terms to be most consistent with the cognitive processes and skills used in a systems thinking approach. Table 1 outlines the characteristics of the two extremes of the continuum. Note that this table is organized such that comparable characteristics are listed side by side (when possible). The characteristics listed in the last three lines of the table describe the types of learners that typically engage in these cognitive processes.

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Table 1. Characteristics of Analytical/Elaborative and Holistic Cognitive Processes.

Characteristics of Analytical/Elaborative Cognitive Processes	Characteristics of Holistic Cognitive Processes
Focused on thinking deeply about parts[57]	Focused on thinking about wholes[57]
Focused on the categories to which an object belongs, its attributes and rules/procedures that govern its behaviors[59-60]	Focused on connections and interrelationships between parts within a whole and on how the interrelationships between parts influence behaviors[57,59]
Bottom-up in nature[61]	Context-driven[61]
Field-independent: Focused on objects and how the properties of the object cause behavior or change[59]	Field-dependent: Focused on how the interaction of object and context results in a change in an object's behavior[59]
	Emphasizes change and multiple perspectives;[59] Focused on multiple potential underlying factors for a given behavior of phenomenon (complexity)[62]
May be more typical of learners from Western cultures (Western education) [57,59,62]	May be more typical of learners from East Asian cultures[57,59,62]
Learners may approach information in a step-wise, piecemeal, or sequential manner[57,63]	Learners may try to construct an overall picture of a situation or system and the connections among its components before trying to solve a problem[57,64]
May be associated with more visible "active" learning classroom behavior because analytical/elaborative learners respond to one part of a problem at a time and will, as a consequence, approach instructors more frequently with questions about individual problem parts[57]	May be associated with the appearance of more passive classroom behavior because holistic learners need to put all the pieces together before approaching an instructor with questions[57]

While there are advantages and benefits to both analytical/elaborative and holistic types of thinking, research suggests that deeper learning occurs when students use both types of thinking to develop an understanding of a given concept or phenomenon.[58,60-61] In fact, Marton[65] suggests that deep understanding (of a system, phenomenon, etc.) requires both an understanding of the parts of the system and of the way that the parts are organized and related to each other (and the principles that drive that organization). Therefore, while a student could, in theory, approach a systems thinking activity from a purely analytical/elaborative perspective or from a purely holistic perspective, we propose that their learning will benefit the most from engaging in a systems thinking activity that requires both types of cognitive processes, a factor we will take into consideration when describing potential uses of our tool.

THE ChEMIST TABLE: CHARACTERISTICS ESSENTIAL FOR DESIGNING OR MODIFYING INSTRUCTION FOR A SYSTEMS THINKING APPROACH

Identification of the Essential Characteristics of Systems Thinking for Chemistry Education

We began our search for the essential characteristics of systems thinking for chemistry education by examining existing definitions and descriptions of systems thinking in the literature. We searched the ERIC (Education Resources Information Center) database for publications that included the keywords “systems thinking” in the title or abstract. Because we were primarily interested in the application of systems thinking in an educational setting, we read the corresponding abstracts in order to select those publications that either (1) provided background about systems thinking itself or (2) focused on the use of systems thinking in educational contexts, particularly in the STEM disciplines. We also searched Google Scholar for the term “systems thinking,” combined, individually, with the name of each of the STEM disciplines. The number of research articles in these areas was limited, so we included conference presentations, as well as some more theoretical pieces or commentaries in our pool of publications to examine. We then identified additional relevant articles through our readings of the ERIC- and Google Scholar-identified documents. Overall, we examined the definitions and descriptions of systems thinking in 115 articles.

As expected, there were many definitions of systems thinking in the literature. Here, we provide a few of those definitions. This selection is not meant to serve as a comprehensive list of all of the different types of definitions of systems thinking,[5] but simply as an illustration of the variety of definitions that exist in the literature. It is worth noting that the examples we have chosen to include here are focused more on definitions of systems thinking used in educational contexts.

- Systems thinking is “an approach for examining and addressing complex behaviors and phenomena from a more holistic perspective.” (ref *1*, p. 2720)
- Systems thinking is both a method for acquiring a coherent understanding of complex phenomena and a learning outcome.[51]
- Systems thinking is “an analytic technique that provides a means by which to understand the behavior of complex phenomena over time” and can be used as both an instructional and problem-solving tool. (ref *20*, p. 195).
- Systems thinking may be considered a cognitive,[32] metacognitve,[38] or higher-order thinking skill[32,48,66] and can be developed through appropriate instruction.
- Systems thinking can be viewed as many things: a perspective, a language with its own unique vocabulary, or a toolset for visualizing and communicating.[67]

Our intention in the current project was not to create a single definition of systems thinking that could be used in all fields. In fact, Castelle and Jaradat[68] have argued that developing a single definition of systems thinking could limit the disciplines in which systems thinking could be implemented. Our goal was to identify a limited set of essential characteristics that could be used to determine if a given chemistry teaching and learning activity was using a systems thinking approach. Our identification of the essential characteristics of a systems thinking approach for chemistry education is in alignment with Bloom’s statement that

> Ideally each major field should have its own taxonomy of objectives in its own language—more detailed, closer to the special language and thinking of its experts, reflecting its own

> appropriate sub-divisions and levels of education, with possible new categories, combinations of categories, and omitting categories as appropriate. (as cited in *ref 69*, p. xxvii-xxviii)

As we read through the various definitions and descriptions in the literature, we identified many different characteristics of systems thinking. We grouped similar characteristics into categories and created descriptions of these categories. In this process, we merged categories for which we were unable to write distinguishable descriptions. Ultimately, we identified five essential characteristics of systems thinking that were particularly useful in the context of chemistry education. We verified that this list was consistent with our guiding principles (see the section entitled "Intent of the Current Project") and checked the essential characteristics, once again, against the definitions and descriptions of systems thinking from the literature.

Below, we list these essential characteristics. We have chosen to phrase them in terms of what a chemistry learner should do during an activity that follows a systems thinking approach because research indicates that the benefits of using a systems thinking approach in an educational context are best achieved through active participation on the part of the students.[13,70-72]

A systems thinker in chemistry education should:

- Recognize a system as a whole, not just as a collection of parts.
- Examine the relationships between the parts of a system, and how those interconnections lead to cyclic system behaviors.
- Identify variables that cause system behaviors, including unique system-level emergent behaviors.
- Examine how system behaviors change over time.
- Identify interactions between a system and its environment, including the human components of the environment.

This set of essential characteristics is both limited in number, which allows for some flexibility in classroom implementation of systems thinking approaches, and consistent with the definitions and descriptions of systems thinking in the literature. It also aligns with Talanquer's[53] key features of chemical systems thinking. In particular, the second, third, and fourth essential characteristics focus on *using mechanistic reasoning to explain chemical phenomena*. The fifth essential characteristic allows students to *situate their chemistry learning in real-world contexts*. Finally, we believe that one of the goals of using systems thinking approaches in chemistry education is to equip learners with the holistic skills necessary to address complex, real-world problems, such as planetary sustainability. A knowledge of the mechanistic causes of chemical phenomena can help students *understand the impacts of their actions* and, ideally, *encourage them to make decisions and take actions* to positively address these problems.

Aligning Systems Thinking Skills with the Essential Characteristics

There are many published lists of cognitive skills associated with systems thinking.[1,5,7] Unfortunately, there is no consensus about which systems thinking skills students should develop.[38] Therefore, having identified the essential characteristics of a systems thinking approach in the context of chemistry education, our next tasks were (1) to align specific systems thinking skills with each of the essential characteristics and (2) to order the aligned skills from more analytical/elaborative to more holistic. The result is presented in Table 2, the ChEMIST (**Ch**aracteristics **E**ssential for designing or **M**odifying **I**nstruction for a **S**ystems **T**hinking approach) table. In this table, the five essential characteristics of a systems thinking approach in chemistry education are listed in the first column. The three columns to the right feature a continuum of skills that can be used to demonstrate a student's engagement in the essential characteristics. It is worth noting that this table does not include all of the cognitive skills that have been associated with systems thinking. It does, however, include skills that align well with the identified essential characteristics and which are widely used across multiple disciplines in which systems thinking is employed. It is also worth noting that many of the essential characteristics and skills are highly interconnected, a feature that is consistent with systems thinking itself.

In the sections that follow, we provide brief descriptions of each essential characteristic and its corresponding skills.

Table 2. The ChEMIST Table: Characteristics Essential for Designing or Modifying Instruction for a Systems Thinking Approach in Chemistry Education

A systems thinker in chemistry education should...	**Systems Thinking Skills*** Less Holistic…… More Analytical/Elaborative……		……More Holistic ……Less Analytical/Elaborative
Recognize a system as a whole, not just as a collection of parts	Identify the individual components and processes within a system	Examine the organization of components within the system	Examine a system as a unified whole
Examine the relationships between the parts of a system, and how those interconnections lead to cyclic system 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
Identify variables that cause system behaviors, including unique system-level emergent behaviors	Identify the multiple variables that influence a given system-level behavior; Consider the potential effects of stochastic and "hidden" processes on the system-level behavior	Examine the relative, potentially non-linear, effects that multiple identified variables have on a given system-level behavior	Identify, examine, and explain (to the extent possible) emergent system-level behaviors
Examine how system behaviors change over time	Identify system-level behaviors that change over time	Describe how a given system-level behavior changes over time	Use system-level behavior-over-time trends under one set of conditions to make predictions about system-level behavior-over-time trends under another set of conditions
Identify interactions between a system and its environment, including the human components of the environment	Identify and describe system boundaries	Consider possible effects of a system's environment on the system's behaviors; Consider how the system under study might be a component of and contribute to the behaviors of a larger system	Consider the role of human action on current and future system-level behaviors

290 * An understanding of complex systems requires both an understanding of the system as a whole and of the components of the system. "Holistic" refers to skills that focus primarily on the system as a whole. "Analytical/Elaborative" refers to skills that primarily focus on the components of a system—not as individual, disaggregated parts---but within the context of the system as a whole. Research suggests that students will benefit the most from systems thinking activities that include <u>both</u> holistic and analytical/elaborative skills.

Essential Characteristic 1

The most basic of the essential characteristics involves a system thinker's recognition that a system is more than just a collection of parts.[1,5,14,32-33,36,38,41,48,51,67,73-85] Although it is important to examine the components of a system, it is also important to examine the system as a whole, as the system may have properties and behaviors that could not have been predicted based on a study of the component parts alone.[84] Behaviors that occur at the system level are typically affected by (1) the components of the system, (2) the organization of the components within the system, and (3) the interactions between the components of the system.[5,67,73-74,79,83] Essential characteristic 1 focuses on the parts of a system and their organization, while essential characteristic 2 focuses on the interactions between the parts of the system.

One cannot understand a system without understanding its component parts.[1,5,9,14,32-33,41,67,78,86-88] In fact, studies focused on the development of systems thinking skills in other disciplines have stated that the ability to identify the components of a system is a prerequisite for developing other systems thinking skills.[32,35,48,80]

Understanding the organization of parts within a system is another key skill associated with systems thinking[1,5,7,9,14,32,35,67-68,76-76,81-83,87,89-93] and prepares learners to understand self-organizing and dynamic properties of the system.[14,35,78,94-95] Understanding the organization of the parts within the system also serves as a foundation for the more holistic skill of understanding and examining a system as a whole.[1,5,7,9,14,32-33,35,67,78,81-82,91,95]

Essential Characteristic 2

As mentioned above, system-level behavior and properties typically result from interactions between the parts of a system.[1,5,7-8,11,14-15,17,23,32-33,34-36,45,48,67,75-78,81-83,86-94,96-101] Essential characteristic 2 focuses on the interconnections between parts and how those interconnections, including positive and negative feedback loops, result in system-level behaviors, many of which are cyclic in nature.

The most analytical/elaborative skill associated with this essential characteristic is the identification of the interconnections between the system's parts.[5,32-33,35,101] In order to identify relevant connections between component parts of a system, learners may first need to acquire an understanding of the properties of the individual components.[32-33,35,80] As such, there is a link between this essential characteristic and essential characteristic 1. We suggest that facilitators of activities that follow a systems thinking approach emphasize that learners should look for multiple connections between a given part and other system parts, as research in the area of systems thinking indicates that learners tend to focus on simple, monocausal relationships when trying to explain a property or behavior of a system.[43-44,46,50,70,102-104] Systems are complex, and there exist multiple interconnections between their parts.

Systems attempt to maintain stability through feedback mechanisms.[1,5,9,21,32,48,67,78,85,88] Complex systems include both positive, or *reinforcing*, and negative, or *balancing*, feedback loops.[23,36,67,81,105] Feedback loops result from interactions between a system's components,[35,87] and learners must first identify and understand feedback loops before they can understand how those feedback loops might contribute to emergent, system-level behaviors and properties.[1,7,11,17,32-33,35,48,67,78,81,97-98,101,106]

In complex systems, behavior generally presents in cyclic patterns.[7-8,11,14,17,32-33,48,67,81,87,94,97-98,106] These cyclic patterns result from the interactions of multiple reinforcing and balancing feedback loops,[7,23,32,36,48,81,97-98] and understanding cyclic behavior requires that learners engage in closed-loop thinking.[23,32-33,36,48,81]

Closed-loop thinking is often contrasted with linear thinking, which is a more typical type of thinking for both learners and people in general.[8,14,23,29,36,50,95] Learners tend to think in simple, linear cause-and-effect terms: that behaviors and properties result from a single, unique cause, instead of being influenced by multiple causes.[43,46,102-103] Most complex systems/problems are not linear. They involve multiple causes, as well as feedback loops and time delays. Closed-loop thinking requires that students consider not just how variable A might affect variable B, but also how the consequent change in variable B will then affect variable A (Figure 2).

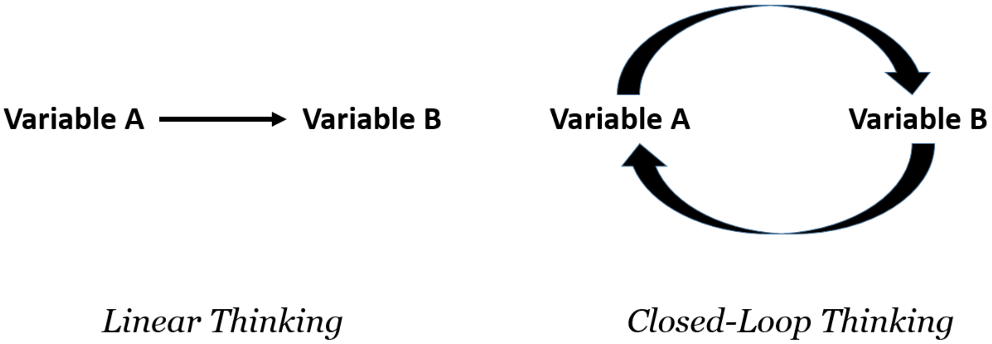

Figure 2. Linear v. closed-loop thinking.

Interestingly, Raia[102] found that asking students to identify and describe patterns in data and then to discuss factors that might have established or maintained that pattern can help students recognize the multiple causes for a given system-level behavior.

Essential Characteristic 3

A key feature of complex systems is the fact that there are often nonlinear relationships between causal variables and system-level behaviors or properties.[14,23,36,38,53,67,83,94,107-108] The concept of nonlinearity is rooted in chaos theory and suggests that a small agitation of the system can be amplified nonlinearly to create a substantial effect elsewhere in the system.[14,36,109] Nonlinearity is counterintuitive for many learners, who assume that a small change in a causal variable will result in a proportionally small change in behavior;[29,71] however, an understanding of nonlinearity may provide learners with a better ability to (1) set system boundaries;[36] (2) identify feedback loops;[35] (3) understand cyclic behavior;[36] and (4) create simulation models to test predictions about system-level behavior.[35] Thus, it is important for students who engage in a systems thinking approach to understand nonlinearity.[7,14,32,78,81,83,87,90,92-93,97-98]

The most analytical/elaborative skill associated with developing an understanding of the nonlinearity of a system is the identification of the multiple variables that affect a system-level behavior of interest. Learners should be encouraged to look for both variables that cause an increase in the level or amount of the system-level behavior and variables that cause a decrease in that behavior. The focus should be on variables that *cause* behavior, as opposed to variables that are *correlated* with behavior.[1,23,77,86,91] It is important to note that, particularly in the context of chemistry education, some of these variables may be “hidden” or unavailable to the senses[32,67,85,95,110-114] and that system-level behaviors can result from stochastic processes.[83] Systems thinkers must be able to recognize and include hidden variables, as well as the potential effects of stochastic processes, when considering system-level properties.[14,32,83,108,115-116] It is also worth noting that complex systems are characterized by distinct, interdependent levels of organization. A change in a variable at one level of organization (say, the submicroscopic level) can result in changes at another level of organization (say, the macro level).[32-33,38,45,85,110,114] For this reason, it is important that systems thinkers develop a sense of scale[78] and think about and between different levels of scales.[5,7,15,36,38,51,53,83,85,87,90,92-93,101,117]

Another skill associated with developing an understanding of systems and their unique, emergent behaviors is examining the *relative* effects of different variables on a given system-level behavior or property of interest, paying particular attention to variables that might have nonlinear effects on that behavior or property.[14,29,71] Complex systems have emergent properties that can only be ascribed to the system as a whole and not to any individual component of the system.[68,79-80,84,95] These unique properties result from interactions between organized parts of the system.[33,45,79,83,85,94,99-100] A simple example of an emergent property familiar to chemists might be the surface tension of a bulk sample of water, a property that cannot be ascribed to an individual water molecule, but that results from the interaction between water molecules.

Emergence is fundamental to science[85] and, specifically, to chemistry;[78,95,118] and, thus, an understanding of emergence is critical for an understanding of scientific phenomena.[85] Understanding emergence has been also been identified as a key feature of systems thinking.[1,7-8,11,14-15,17,32,67-

[68,78,81,83,87,90-93,97-98,106] An understanding of emergence is challenging and is predicated on an understanding of interacting feedback loops and nonlinear behavior.[5,14,32,35,71,83,108,115-116]

Essential Characteristic 4

Complex systems and their properties are dynamic.[14,85] Thus, a key skill of systems thinkers is the ability to recognize and describe the dynamic interactions and behaviors in a system.[1,5,7-8,11,14-15,17,20,32-33,48,67,78,81,83,87,90,92-93,97-98,106]

Dynamic thinking allows complex problems to be considered as patterns of system behavior over time.[23,37] A knowledge of how system behaviors change over time, along with an understanding of the interactions of the various feedback loops that exist within a system, allows for a deeper understanding of the mechanistic causes of a behavior. It also allows provides a foundation for predictions about future behaviors of the system or about how the system will behave under different sets of conditions.[1-3,5,7,11,17,35,67,81] It should be noted that predicting the behavior of a complex system in the future or under a different set of conditions can be very challenging, particularly as more variables and more feedback loops become involved.[71] We believe, however, that even the attempt to make predictions about the future behavior of a system can lead to a greater understanding of the system and its properties.

Essential Characteristic 5

Those studying a complex system must define the boundaries of the system,[78,96] and it is often most useful to establish system boundaries that include only the components and interrelationships affecting a system-level behavior of interest.[1,7,36,38,68,75,77,91] In fact, Aubrecht et al.[105] suggest that learners not only identify boundaries, but question if the boundaries that have been defined are those that are most useful for the question or behavior under study.

While the system may be the main focus of study, it is important to realize that (1) the system is influenced by its environment;[7,96] (2) a given system is connected to other systems;[1,77,83,91,94,99-100] and (3) a given system may be a component nested within a much larger system.[1,51,78,86,96] In fact, emergent properties of one system may be seen as the properties of the individual components of larger systems.[14] As such, part of a systems thinking approach should include not only a consideration of the system itself, but (1) how the system affects and is affected by its environment and (2) how the system under study might be a component of and contribute to the behaviors or properties of a larger system.

Ossimitz states that “systems thinking also always has a pragmatic component: it deals not just with contemplating the system, it also is interested in system-oriented action” (ref *81*, p. 9). Accordingly, it is important that learners consider any impacts that human action (in terms of physical actions, policy decisions, etc.) might have on a system’s behavior, whether humans have been defined as part of the system under study or as part of the system’s environment.[48,68,81] Ultimately, the proponents of systems thinking suggest that a knowledge of how and why a system behaves as it does—and how human actions and policies affect the behavior of a system—will prepare learners to understand the ethical dimensions of human activity[21,78] and to make changes through collaboration, democratic participation, and ethical action to address the complex global problems we encounter today, such as poverty, world hunger, and climate change.[1,23,53,68,76-77,86,119]

PROPOSED USES OF THE ChEMIST TABLE

We envision four potential uses of the ChEMIST table. First, the table can be used to *design* a new systems thinking activity. Second, the table can be used to *analyze* existing activities and curricula in order to determine if they are consistent with a systems thinking approach. Third, for activities and curricula that have already been determined to align with a systems thinking approach, the table can be used to *optimize* the combination of skills in which students engage during the activity. Finally, the table can be used to *educate* students about systems thinking and systems thinking skills. We will briefly touch on each of these potential uses in the sections below. A more detailed example of the use of the ChEMIST table to develop and optimize a systems thinking activity can be found in supplemental materials.

Design of New Systems Thinking Activities

In our development of the ChEMIST table, we have identified five essential characteristics of activities that follow a systems thinking approach in chemistry education. The characteristics are essential in that all five of these characteristics need to be represented in an activity if it is to be considered a systems thinking activity. We recognize that many activities in chemistry and science education take place over the course of multiple days or class periods. It is not necessary that each of the essential characteristics be represented during each day of an extended activity, but that each of the essential characteristics be represented at some point during the course of the activity.

Let's suppose that an instructor wishes to develop a systems thinking activity. A first step would be to identify a potential chemistry concept or phenomenon that could be the basis of that activity.[97] Both Richmond[36] and Goodman[120] note that, as systems thinking is concerned with change in behaviors over time, it would be most useful to employ systems thinking to examine problems or phenomena that unfold over time or have a time/dynamic dimension to them.

Having identified a chemical phenomenon on which to base the systems thinking activity—and the chemical system that exhibits that phenomenon—the instructor could then use the five essential characteristics from the left-hand column of the ChEMIST table to guide their development of the activity. For example, they might ask themselves questions like those listed in the bullet points below. Each bullet point includes questions that relate to one of the five essential characteristics included in the operational definition of systems thinking:

- What are the parts of the system that I want my students to examine? How are those parts organized in the system? What can I ask my students to do to examine those parts and their organization?
- What types of interconnections exist between the parts of system? What can I ask my students to do that will help them recognize the negative and positive feedback loops that exist within the system?
- Which variables cause the chemical phenomenon I want my students to understand? Which hidden variables or processes contribute to the phenomenon? How can I help my students consider the impacts of stochastic processes on the phenomenon? What type of activity could I use to help my students determine the relative impacts of different causal variables?
- How does the chemical phenomenon I want my students to examine change over time? How can students model the behavior over time and attempt to use that model to make predictions about how the system will behave under another set of conditions?
- What are the boundaries of the system I am asking my students to study? How is this system part of a larger system? What sort of an activity will allow my students to examine the impact of this chemical phenomenon on their lives or how the choices they make in their everyday lives affect this chemical phenomenon?

The instructor's answers to questions like those listed above can provide the foundation for the design of a systems thinking activity. Once a draft of that activity is generated, the instructor may want to analyze the activity to verify that it does, indeed, include each of the essential characteristics before trialing it with their students. Such an analysis is briefly described in the following section.

Analysis of Existing Activities and Curricula

While the ChEMIST table could certainly inform the development of a new systems thinking activity, it could also be used to determine which of the essential characteristics are already present in and which are missing from an existing learning activity. Such an analysis could focus instructors' efforts on modifications to add missing essential characteristics.

Instructors using the ChEMIST table for this purpose would focus mainly on the left hand column of the table, the list of the essential characteristics. For example, perhaps an instructor examines an existing activity, with the results of the analysis being presented on a simplified form of the ChEMIST table, as shown in Figure 3.

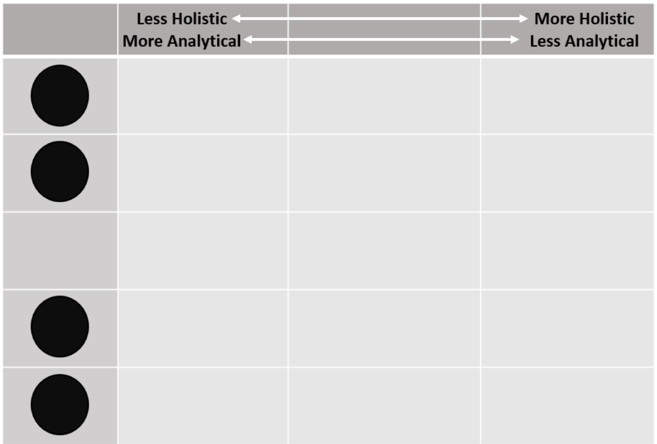

Figure 3. Illustration of the use of the ChEMIST table for analyzing existing activities and curricula.

According to the instructor's analysis, the activity already engages students in essential characteristics 1, 2, 4, and 5. In order to make the activity consistent with a systems thinking approach, they can focus their efforts on additions or modifications that engage students in essential characteristic 3 (Identify variables that cause system behaviors, including unique system-level emergent behaviors).

Optimizing Activities that Follow a Systems Thinking Approach

The ChEMIST table presents three different skills through which students can demonstrate their engagement in each of the essential characteristics. The skills are ordered from more analytical/elaborative on the left to more holistic on the right. As mentioned previously, research indicates that learning is optimized when students engage in both analytical/elaborative and holistic skills when studying a topic or analyzing a system.[58,60-61,65] Therefore, we believe that the ChEMIST table could be used to optimize students' learning during an activity that follows a systems thinking approach or, if students engage in multiple systems thinking activities over the course of a semester, to ensure variety in the skills students employ during the course. An instructor using the ChEMIST table for this purpose would focus on the last three columns of the table.

Let's assume that the instructor described in the previous section has modified their existing activity so that all five essential characteristics are now present. They now might examine the activity from the perspective of the specific skills in which students engage during the activity. The analysis might result in Figure 4.

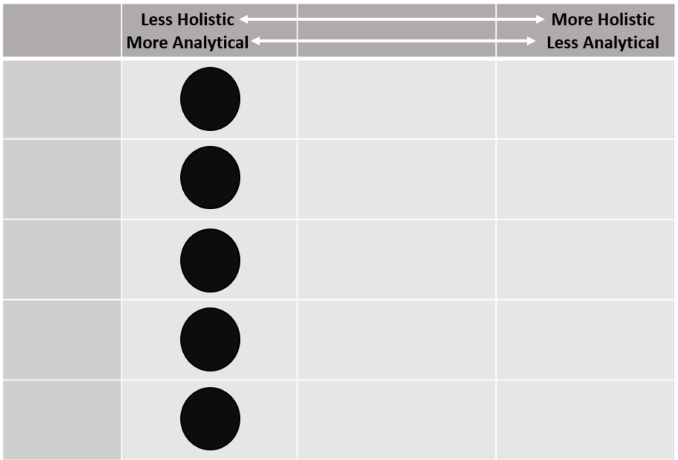

Figure 4. Illustration of the use of the ChEMIST table for optimizing systems thinking activities and curricula: Skill analysis.

The instructor's analysis indicates that they, whether intentionally or not, have engaged students in only the skills on the analytical/elaborative end of the scale. To optimize their students' learning, they may choose to alter some of the components of the activity so that students engage in some analytical/elaborative skills, some intermediary skills, and some more holistic skills (Figure 5).

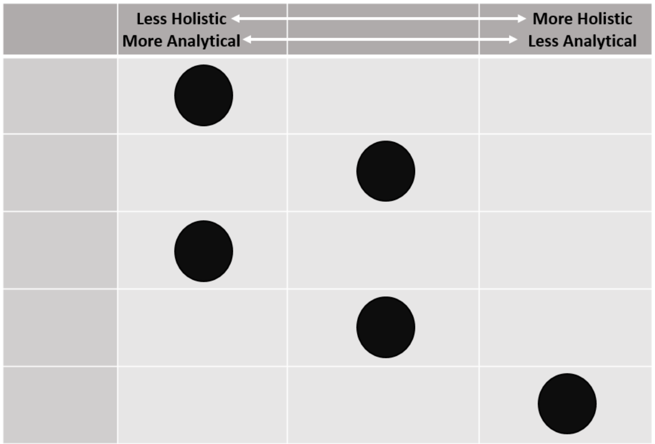

Figure 5. Illustration of the use of the ChEMIST table for optimizing systems thinking activities and curricula: Skill optimization.

For example, with reference to essential characteristic 4, the instructor might choose to identify system-level behaviors that change over time for their students but ask the students to describe how those behaviors change over time, an intermediary skill.

Should the instructor use another systems thinking activity during a particular course, they may choose to engage the students in different skills for that activity (Figure 6).

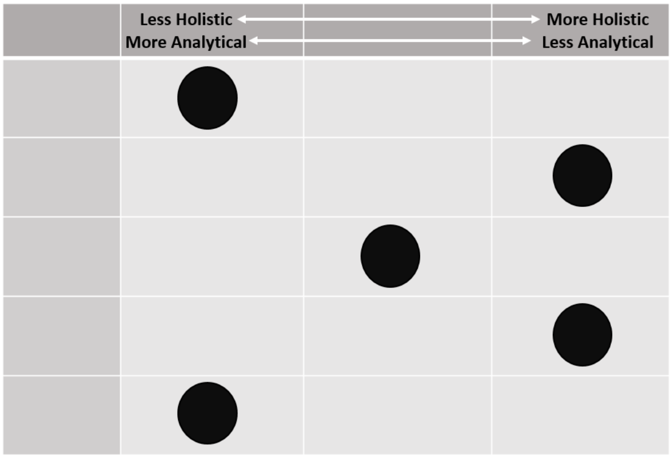

Figure 6. Illustration of the use of the ChEMIST table for optimizing systems thinking activities and curricula: Skill variation.

Educating Students about Systems Thinking and Systems Thinking Skills

Finally, instructors might provide the ChEMIST table to their students as a means of helping them understand what systems thinking is and which cognitive skills are involved in systems thinking. Research suggests that systems thinking is often not consistent with the typical ways that people think.[50] As such, systems thinking and systems thinking skills must be explicitly taught.[44,104] Students need explicit scaffolding and direction in order to both develop systems thinking skills and to be able to transfer those skills to other learning environments.[13,70-71] Moreover, students need to be explicitly told why a systems thinking approach is being used and about the benefits of employing a systems thinking approach.[121] They also need to be told why they are being asked to engage in both analytical/elaborative and holistic skills.[58,60-61,65] Otherwise, they may not persist in the challenging task of examining material from a systems thinking approach. An instructor might provide the ChEMIST table to students—and facilitate a discussion about systems thinking characteristics and skills—to help the students understand what is being asked of them in a systems thinking activity and to determine if they have achieved those outcomes.

THOUGHTS ABOUT THE RELATIONSHIP BETWEEN SYSTEMS THINKING AND OTHER APPROACHES TO CHEMISTRY EDUCATION REFORM

Researchers and scientists alike have critiqued typical modes of chemistry education, saying that they don't motivate students, promote meaningful learning, or prepare students to use their chemistry knowledge in the real world. For example, recent publications have described chemistry education as being disconnected, fragmented, shallow, algorithmic, and decontextualized.[1,122-126]

Multiple efforts have been made to address these criticisms and improve the outcomes of chemistry education. While we note that it is particularly challenging to completely disentangle content from the way in which it is presented, we find that there are two broad categories of approaches that have taken been taken to reform chemistry education, some of which we highlight here.[123,125,127] The first group of approaches have focused primarily on reforming the pedagogies used in chemistry courses including, for example, POGIL (Process Oriented Guided Inquiry Learning),[128] PLTL (Peer-Led Team Learning), [129] context-based learning,[130-131] problem-based learning (PBL),[132-133] case-based learning (CBL), [134] and argument-driven inquiry (ADI).[135] Other reform efforts have focused primarily on the content of chemistry courses, identifying content that is essential for students to learn and then organizing that content into limited themes or groupings that are revisited throughout a course or program of study. Examples of this type of approach to chemistry education reform include the Chemistry, Life, the Universe, & Everything (CLUE) curriculum,[123,136] the Chemistry Unbound curriculum;[127] and the Chemical Thinking curriculum.[137-138]

Systems thinking has been proposed as yet another effort to address some of the criticisms of chemistry education,[1,72,78,124] but how does it compare with other recent reform efforts? Which aspect of chemistry education does it address? Does it address the way chemistry is taught (pedagogy)? Does it address the structure and organization of chemistry content within a course or curriculum? Does it address something else? We find these important questions to answer for two reasons: (1) if systems thinking is the same as another, existing approach to chemistry education, there is no need to duplicate efforts; and (2) if systems thinking is different from existing approaches, it is important to consider the ways in which systems thinking might complement these existing approaches. In the paragraphs below, we briefly discuss our thinking as we have attempted to answer these questions for ourselves, as well as the conclusions we have reached. Please note that this discussion is not comprehensive or final. We present this information as the start of a community-wide conversation about distinctions between systems thinking and other approaches to chemistry education reform.

Can Systems Thinking Be Distinguished from Other Approaches to Chemistry Education Reform?

Most of the approaches to chemistry education reform mentioned in the previous paragraphs are easily distinguishable from a systems thinking approach. However, some—including context-based learning, problem-based learning, project-based science, and case-based learning—have been either confused or conflated with a systems thinking approach. Interestingly, these all belong to a family of relatively similar, problem-based pedagogies.[132-133,139] While it is true that each of these pedagogies shares a context-based focus with a systems thinking approach, we would argue that they are very different from a systems thinking approach in their essential characteristics.

Let us consider context-based learning, as this approach has a particularly rich history of use in chemistry education.[130-134,140-143] We acknowledge that there are many definitions and implementations of context-based learning, even in the specific context of chemistry education. For the sake of discussion, we will refer to the characteristics Gilbert[141] described as being essential for *full* implementation of context-based learning in chemistry education. Table 3 shows these essential characteristics of context-based learning, alongside the characteristics we have identified as being essential to a systems thinking approach.

Table 3. Essential characteristics of a systems thinking approach and a context-based learning approach. [Common characteristic is highlighted with italicized text.]

Systems Thinking Approach	Context-Based Learning Approach
Recognizes a system as a whole, not just as a collection of parts	*Situates a learning activity within a relevant, real-world context*
Examines interconnections and relationships between the parts of a system, and how those interconnections lead to cyclic system behaviors	Engages students in a community of practice with a high level of interaction (student-student and student-teacher)
Identifies variables that cause system behavior, including unique system-level emergent behaviors	Addresses chemically important concepts and requires that students participate in chemistry-relevant tasks
Examines how system behaviors change over time	Engages students in chemistry-specific language
Identifies interactions between a system and its environment, including the human components of the environment	Builds on students' prior knowledge

Based on the information in Table 3, it is apparent that the only essential characteristic that a systems thinking approach shares with that of a context-based learning approach in chemistry education is a focus on contextualization (italicized characteristics in Table 3).

> ***Conclusion 1:*** *Systems thinking is distinct from other approaches to chemistry education reform and, therefore, may offer distinct benefits for student learning or support distinct learning outcomes.*

Which Aspect of Chemistry Education Does a Systems Thinking Approach Address?

As mentioned previously, there have been two major groupings of chemistry education reform efforts. Although both address issues related to content and pedagogy, one focuses primarily on improving the pedagogy through which chemistry content is presented and the other focuses primarily on improving the structure and organization of chemistry content throughout a course or program of study. If we consider the essential characteristics of a systems thinking approach (Table 3), we find that they do not focus on how chemistry is taught. Therefore, a systems thinking approach does not fit with the grouping of chemistry education reform efforts focused on pedagogy. Likewise, a systems thinking approach does not propose to structure or organize chemistry content into themes. Therefore, it does not fit with the second grouping of chemistry education reform efforts. Which aspect of chemistry education *does* a systems thinking approach address, then?

We argue that systems thinking can be thought of as a lens or tool for analyzing and making sense of chemical phenomena. In other words, it provides a framework of guiding skills and tasks that instructors and students alike can use when trying to make sense of chemical concepts and phenomena. From this perspective, systems thinking could be considered a type of crosscutting concept. Cooper,[34] in a discussion of the current understanding of the Next Generation Science Standards (NGSS) Crosscutting Concepts (CCCs), identifies three potential purposes of the CCCs in science education. We see one of these, CCCs as "tools and lenses," as being very coherent with the operational definition of systems thinking we have presented in the current paper. According to Cooper (*ref* 34, p. 905),

> a lens provides a way to focus on a specific aspect of a phenomenon which can require a student to think more deeply and explore that phenomenon in a specific way [and] a CCC used as a tool allows students to participate in an analysis that can make sense of the phenomenon.

Although it is true that systems thinking might be thought of as a crosscutting concept by the description provided by Cooper,[34] we are hesitant to refer to it as such because of potential confusion with the NGSS CCCs. The NGSS includes a CCC by the title of "Systems and Systems Modeling." This CCC focuses on the importance of recognizing, examining, and modeling systems, but provides little guidance for *how* to analyze or make sense of systems. Thus, although the CCC includes some aspects of systems thinking, it is not completely consistent with a systems thinking approach.

In fact, systems thinking, as operationally defined in this paper seems to overlap not only with the "Systems and Systems Modeling" CCC, but with aspects of each of the NGSS CCCs. In the bullet points below, we briefly outline some of the ways in which a systems thinking approach aligns with the NGSS CCCs. The words and phrases in bold font represent the NGSS CCCs (for an extended description of the CCCs, please see *ref* 144):

- **Patterns.** Via a systems thinking lens, students examine chemical phenomena in terms of patterns in the organization of system components (Essential Characteristic 1) and in terms of patterns in system-level behavior over time (Essential Characteristics 2 and 4).
- **Cause and effect: Mechanism and explanation.** Via a systems thinking lens, students examine the potential causes of system-level behavior (Essential Characteristics 2 and 3) and use their knowledge of these causes to make predictions about system-level behavior (Essential Characteristic 4).
- **Scale, proportion, and quantity.** Via a systems thinking lens, students consider the effects of "hidden" processes, including those that occur at different scales (Essential Characteristic 3).
- **Systems and system models.** Via a systems thinking lens, students identify boundaries for systems and the potential effects of a system's environment on system-level behaviors (Essential Characteristic 5). Students can also model their understandings of the causes of cyclic, system-level behavior in order to make predictions about the behavior of the system under an alternate set of conditions (Essential Characteristic 4). As a part of their study of a system-level behavior, students examine the components of a system, their organization, and the interactions between them in order to explain emergent, system-level properties (Essential Characteristics 1 and 2).
- **Energy and matter: Flows, cycles, and conservation.** Via a systems thinking lens, students can consider the effects of energy and matter flows into and out of a system on system-level behavior (Essential Characteristics 3 and 5).
- **Structure and function.** Via a systems thinking lens, students consider how the organization of system components (Essential Characteristic 1) and the interactions between these components (Essential Characteristic 2) contribute to system-level behavior.
- **Stability and change.** Via a systems thinking lens, students consider how positive (reinforcing) and negative (balancing) feedback loops result in (1) cyclic patterns of system-level behavior over time, (2) a change in the system-level behavior, or (3) the stability of a system-level behavior (Essential Characteristics 2 and 4).

Even though a systems thinking approach includes aspects of *all* of the NGSS CCCs, the fact that the CCC "Systems and Systems Modeling" includes the word "systems" creates the possibility that it will be conflated with systems thinking. For this reason, we propose that, in the context of chemistry education, it might be better to refer to systems thinking as a tool or lens for analyzing and making sense of chemical phenomena than to refer to it a "crosscutting concept."

Conclusion 2: *Systems thinking can be used as a lens or tool for analyzing and making sense of chemical phenomena.*

Because the essential characteristics of a systems thinking approach provide a tool or a lens for analyzing and making sense of chemical phenomena, we propose that systems thinking is an approach that is complementary to, but not competitive with, other approaches to chemistry education reform. For example, we can imagine a POGIL activity guided by the essential characteristics of systems thinking and the skills listed in the ChEMIST table. We can also picture using a systems thinking approach to support students' sense making about topics related to change and stability in the CLUE curriculum. Overall, there are many possibilities for synergistic interactions between a systems thinking approach and other pedagogical or content-based approaches to chemistry education reform. We hope that this discussion provides a starting place for exploring those interactions.

Conclusion 3: *Systems thinking can be used as a complement to existing pedagogical or content-based reform efforts in chemistry education.*

CONCLUSIONS

Recent publications suggest that the use of a systems thinking approach in chemistry education has the potential to (1) help students learn chemistry more meaningfully and (2) prepare current chemistry students for future participation in informed and ethical actions to address global issues such as sustainability.[22,25,145] The move toward practically implementing systems thinking approaches, however, remains challenging because there are few examples of systems thinking activities in the discipline and because there have not previously been clear guidelines about what a systems thinking approach looks like in the context of chemistry education. With the creation of the ChEMIST table, we hope that we have provided some guidance for instructors about the characteristics that are essential for a systems thinking approach in chemistry education, as well as particular cognitive skills through which students can demonstrate their engagement in the characteristics.

It is worth noting that the ChEMIST table was developed with specific goals and a specific audience in mind. We intended to identify a limited set of characteristics that could be used to distinguish a systems thinking approach in chemistry education, while still allowing for maximum flexibility in the implementation of the approach. The five essential characteristics of a systems thinking approach—and their associated cognitive skills—are consistent with published definitions and descriptions of systems thinking from the literature and address some of the specific needs of chemistry teaching and learning.[53] That said, it is entirely possible that, for example, a physics educator or a biology educator would identify a slightly different list of essential features and cognitive skills for describing a systems thinking approach in those disciplines.

Finally, while the ChEMIST table has been constructed based on the literature and, therefore, provides a reasonable set of guidelines for designing, analyzing, or optimizing activities for a systems thinking approach in chemistry education, it needs to be trialed with instructors who are implementing systems thinking approaches in real, complex classrooms and then modified based on their feedback.[146] We therefore propose that the ChEMIST table be seen as a living document that will be adjusted for the needs of the community as we continue to learn more about implementing and assessing a systems thinking approach in chemistry education.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI:

10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.]

Using the ChEMIST Table to Design, Analyze, and Optimize Chemistry Instruction for a Systems Thinking Approach: An Abbreviated Example (PDF)

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