ACS Editors' Choice

JOURNAL OF CHEMICAL EDUCATION

Article

Cite This: J. Chem. Educ. 2019, 96, 2720−2729

pubs.acs.org/jchemeduc

Introduction to Systems Thinking for the Chemistry Education Community

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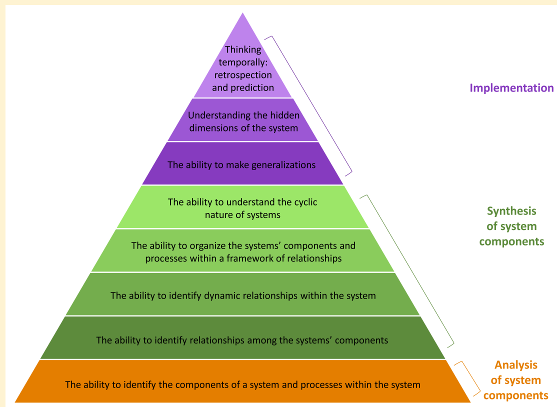
ABSTRACT: Within recent history, both science research and science education have been largely reductionist in perspective. While the reductionist approach has resulted in a significant increase in our knowledge of the natural world and in great technological advances, it is not sufficient for addressing global world challenges, such as sustainability, pollution, climate change, and poverty. We, as members of the Systems Thinking in Chemistry Education (STICE) project, argue that for science in general, and chemistry in specific, to continue to advance and for citizens to be prepared to participate knowledgeably and democratically in science-related policy decisions, the reductionist approaches that are commonly used in chemistry research and chemistry education must be complemented with a more holistic approach. Systems thinking is such an approach. This article discusses the historical development, describes the key characteristics, and presents some skills and competencies associated with systems thinking. Our intention is to provide chemical educators with enough basic information about systems thinking that they can consider why and how such an approach might be applied in the education of both future chemists and future global citizens.



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

■ INTRODUCTION

Within recent history, both science research and science education have been largely reductionist in perspective. While the reductionist approach has resulted in a significant increase in our knowledge of the natural world and in great technological advances, it is not sufficient for addressing global world challenges, such as sustainability, pollution, climate change, and poverty.[1] We, as members of the Systems Thinking in Chemistry Education (STICE) project, along with others, argue that for science in general, and chemistry in specific, to continue to advance and for citizens to be prepared to participate knowledgeably and democratically in science-related policy decisions, the reductionist approaches that are commonly used in chemistry research and chemistry education must be complemented with a more holistic approach.[2−21]

With the current article, we intend to introduce the chemistry education community to *systems thinking*, an approach for examining and addressing complex behaviors and phenomena from a more holistic perspective. We start by identifying some of the consequences and limitations of reductionist approaches. After this, we will discuss the historical development and characteristics of systems thinking approaches.

■ REDUCTIONIST APPROACHES IN SCIENCE AND SCIENCE EDUCATION

Fang and Casadevall describe reductionism in scientific research as "the idea that complex systems or phenomena can be understood by the analysis of their simpler components" (ref 22, p 1401). Reductionist perspectives dominate much of our thinking. For example, the Newtonian perspective is a reductive view of the world. It assumes that objective knowledge is possible and that analysis is the means to achieve such knowledge. From this viewpoint, the world can be explained by linear cause-and-effect relationships such that nature becomes deterministic and predictable (ref 23, p 6):

> *Each of us lives and works in organizations designed from Newtonian images of the universe. We manage by separating things into parts, we believe that influence occurs as a direct result of force exerted from one person to another, we engage in complex planning for a world that we keep expecting to be predictable, and we search continually for better methods of objectively perceiving the world.*

The reductionist perspective of science has, in turn, had an effect on science education. MacInnis explains (ref 24, p 8):

Special Issue: Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry

Received: February 27, 2019
Revised: May 15, 2019
Published: June 6, 2019

DOI: 10.1021/acs.jchemed.9b00169
J. Chem. Educ. 2019, 96, 2720−2729

In a reductionist framework the intent of the educational process is to pass on, or to transfer, what is known by the teacher to the student. This model is based on reductionist assumptions that knowledge is made up of elementary units of experience which are grouped, related, and generalized, and that the parts of a given learning experience are equal to the whole. In this model, which units are to be taught and in what sequence they will be presented is determined by the teacher or a curriculum specialist.

Consequences and Limitations of Reductionist Approaches

Reductionist approaches in science have been very successful in increasing our knowledge of the natural world. They have allowed scientists to reduce complex problems, making them easier to study and understand. Through these approaches, scientists have increased their measurement capabilities and have developed the technologies on which we rely daily.[1,25,26] There are, however, limitations of reductionist approaches, as British author Douglas Adams points out somewhat comically (ref 27, pp 135−136):

Since Newton, we had proceeded by the very simple principle that essentially, to see how things work, we took them apart. If you try to take a cat apart to see how it works, the first thing you have in your hands is a nonworking cat. Life is a level of complexity that almost lies outside our vision.

As the common saying goes, a whole is often more than the sum of its parts, and scientists who focus only on parts are likely to miss important interrelationships between parts or unique properties and behaviors that result from the interactions between parts.

Reductionist approaches in science education, initially developed in order to increase the number of students in science and technology professions in the post-Sputnik era, have also had some positive consequences.[1] For example, these approaches have allowed for the development of both useful cognitive strategies and standardized assessment methods.[24,25] The reduction of "knowledge" to a series of neutral, context-free facts that can be learned and assessed also has associated limitations and challenges.[25] First, and perhaps most importantly, reductionist approaches are not consistent with how people learn.[24,25,28] The reductionist framework suggests that students can learn discrete, unconnected facts out of context and that, by understanding the facts within a discipline, they will come to understand the discipline as a whole. Research, on the other hand, indicates that students learn most meaningfully when they are able to connect new knowledge to previously learned information and when they learn information in the context in which it applies.[28] Reductionist approaches to education also suggest that facts should be learned in the silos of individual disciplines.[25] As a consequence, some critics claim that the reductionist approach keeps students from learning how to generalize what they have learned or how to apply knowledge and skills in new contexts.[24] Finally, reductionist approaches claim an objective view of scientific knowledge and, thus, ignore the human influence on how science is done and how scientific data is interpreted.[24]

■ SYSTEMS THINKING APPROACHES

Systems thinking is an approach for researching and learning about concepts from a holistic perspective. We wish to emphasize that we are not proposing that systems thinking approaches *replace* reductionist approaches, but, rather, that they be used to *complement* reductionist approaches in both chemistry research and chemistry education.[1,22,26] Our view is consistent with that of Meadows (ref 29, p 6):

I do not think the systems way of seeing is better than the reductionist way of thinking. I think it is complementary, and therefore revealing. You can see some things through the lens of the human eye, other things through the lens of a microscope, others through the lens of a telescope, and still others through the lens of systems theory. Everything seen through each kind of lens is actually there. Each way of seeing allows our knowledge of the wondrous world in which we live to become a little more complete.

We believe that systems thinking approaches will be particularly important for educating future global citizens. As we have mentioned, many of the challenges facing mankind now, like sustainability, are global and holistic. In order to address these grand challenges, we need chemists who are trained with a systems thinking perspective. Chemists play a central role in creating innovative technologies and products that allow us to live as we do today. However, our current practices of production and consumption are not sustainable. We need future chemists to be able to think holistically and systematically about chemistry in order to maximize resource efficiency while minimizing hazards and pollution. We also need citizens who can make evidence-based decisions about science-related policy and about how they will interact in and with the planet. These needs can be met by including systems thinking approaches in chemistry education (ref 30, p 24).

If individuals are to become more actively engaged in the decisions that shape their lives, they need to have a sense of ownership in the process, instead of passively deferring to the "expertise" of those in leadership positions. [...] Systemic knowledge fosters the ability to communicate effectively, to ask meaningful questions, and to listen to alternative points of view. The cultivation of skills in dialogue and collaboration is key to the development of participatory decision-making processes, as well as the emergence of a more truly democratic society.

In the sections that follow, we discuss the historical development and some key characteristics of systems thinking approaches. We also describe some of the skills and competencies in which systems thinkers typically engage, along with applications of those skills in a chemistry education context. Our intention is to provide chemical educators with enough basic information about systems thinking that they can consider why and how such an approach might be applied in the education of both future chemists and future global citizens. Many of the topics that will be introduced here will be further discussed in other articles in the current issue.

■ DEVELOPMENT OF THE GENERAL SYSTEMS THEORY AND FOUNDING OF THE INTERNATIONAL SOCIETY FOR SYSTEMS SCIENCES

Modern systems thinking approaches have their roots in the mid-20th century.[6,31] Although systems thinking has been influenced by concepts, philosophies, and methods from multiple fields, including sociology, philosophy, organizational theory, and feedback thought, many significant developments were informed by the field of biology.[30] In this section we highlight some of the key historical figures and events involved in the development of systems approaches to research and thinking. For those who wish to know more, we refer readers to

DOI: 10.1021/acs.jchemed.9b00169
J. Chem. Educ. 2019, 96, 2720−2729

Debora Hammond's comprehensive discussion of the historical development of systems approaches.[32]

Ludwig von Bertalanffy is generally considered the father of systems approaches.[6,33] Bertalanffy was an Austrian biologist who, in response to the largely reductionist approaches used in biological research in the early 20th century, suggested that a complete understanding of organisms must focus not only on the parts of organisms, but also on their wholes. He indicated that organisms have unique properties, characteristics, and behaviors that result from the organization of and interactions between their parts. Further, he stressed that these unique, emergent properties cannot be predicted on the basis of the properties of the parts alone,[32] referencing a quotation from British physicist Sir Arthur Eddington (ref 34, pp 103−104):

> *We often think that when we have completed our study of one we know all about two, because "two" is "one and one." We forget that we still have to make a study of "and" [...] that is to say, of organization.*

Bertalanffy was interested in many different fields of study, including chemistry, physics, biology, sociology, and psychology. He noticed that, within these different fields, there were *systems* that, similar to organisms, displayed emergent properties that could not have been predicted solely on the basis of an understanding of the parts of the system. Based on these observations, he proposed that there are certain underlying rules and principles that guide the emergence of properties at the systems level and that these rules and principles are not unique to a biological context, but are generally applicable in all fields.[6,32,35] Bertalanffy first presented his ideas about a "General Systems Theory" in a philosophy seminar at the University of Chicago in 1937, publishing them formally in 1948, after the end of World War II.[32]

As Bertalanffy developed his ideas about a General Systems Theory, other researchers were searching for theories that would either unify science fields or that would unify the natural and social science fields.[33] Many of these researchers also had connections to the field of biology, including Ralph Gerard (neurobiology), James Grier Miller (psychology and medicine), and Anatol Rapoport (mathematical biology). Others came from nonbiological fields. One of these was Kenneth Boulding, an economist.[33]

Like Bertalanffy, Boulding was interested in many different fields of study and was a strong believer in the importance of alternative perspectives and approaches.[32] Accordingly, he looked to other disciplines for concepts and philosophies that would allow for a more complete understanding of his own field, organizing a unique series of seminars at the University of Michigan between 1949 and 1956. Each seminar focused on a theme, and Boulding would invite presenters from multiple disciplinary backgrounds to provide their perspectives on the theme. For example, the seminar in the 1949−1950 academic year focused on competition and cooperation. Boulding invited biologists to talk about the relationships among plants, animals, and their environments. He invited political scientists to talk about the interactions between political parties. The 1952−1953 seminar, which focused on growth theory, included discussions of crystal growth, nuclear decay, growth of buildings, and growth patterns in the natural world. After the growth seminar, having read Bertalanffy's article about General Systems Theory, Boulding contacted Bertalanffy to enquire about the possibility of forming a society of individuals interested in research about systems. Bertalanffy agreed and started contacting others who might be interested in such a group.[32]

The idea for a society focused on systems research was further discussed by scholars involved in the inaugural cohort of the Center for Advanced Study in the Behavioral Sciences at Stanford University in 1954. Bertalanffy, Boulding, Gerard, and Rapoport were present at this meeting. The society was first conceptualized as the Society for the Advancement of General Systems Theory in 1955/56 and became known as the Society for General Systems Research in 1957. Since 1988, the society has been known as the International Society for the Systems Sciences (ISSS).[32,33] Its stated purpose is to (ref 36):

> *...promote the development of conceptual frameworks based on general system theory, as well as their implementation in practice. It further seeks to encourage research and facilitate communication between and among scientists and professionals from various disciplines and professions at local, regional, national, and international levels.*

■ CHARACTERISTICS OF SYSTEMS THINKING APPROACHES

General Systems Theory, as conceived by Bertalanffy and his colleagues, is not a "theory", as this term is typically used in a scientific context. It has no explanatory power. Rather, it is an approach for studying and understanding the complex world around us.[32] It provides an organizational framework for scientific concepts and for research and learning about these concepts.[6] This framework, according to Bertalanffy, provides a new way of viewing science, thus influencing what we focus on in both science research and learning, our ways of doing science, and our understanding of science itself.[31,32]

Science research and learning, as informed by a systems thinking perspective, focus on the following:

- a system as a whole and not just as a collection of parts;[2,30,32]
- how system behavior changes over time;[2,15,37]
- variables that *cause* system behavior and not variables that are *correlated* with systems behavior;[31,37]
- the organization and interrelationships between the parts in the system;[2,30−32,38]
- how the organization and interrelationships between the parts of the system result in unique emergent properties at the system level;[4,11,31,39]
- the interaction between a system and its environment (including the human components of the environment);[30,31] and
- collaboration, democratic participation, and ethical action.[30,32]

It may be somewhat easy to imagine what a systems thinking perspective looks like in a chemistry research setting, but what does a systems thinking perspective look like in a chemistry *education* setting and how does this approach differ from more traditional approaches or from other similar approaches? According to Jegstad and Sinnes (ref 40, p 667)

> *In chemistry education, a systems thinking perspective may be achieved by investigating environmental, social and economic factors in addition to the chemical content of a specific case. Moreover, the case may be connected to both local and international issues, thereby calling for systems thinking on a global scale as well.*

While we agree that a systems thinking approach will certainly connect chemical content to context, we argue that a systems thinking approach implies specific learning foci that extend a context-based approach. Consider the following simplified

DOI: 10.1021/acs.jchemed.9b00169
J. Chem. Educ. 2019, 96, 2720−2729

example, meant to illustrate how a systems thinking approach might differ from other approaches. We have intentionally left out some of the details related to the chemical content in order to highlight the characteristics of systems thinking approaches in the context of information typically taught in a General Chemistry course.

A common demonstration in a General Chemistry classroom is the exothermic dimerization of the reddish-brown gas NO_2 to the colorless gas N_2O_4.[41] The former is favored at higher temperatures, and the latter is favored at lower temperatures. Reductionist approaches to the teaching of chemistry identify, simplify, sequence, and focus on key chemical concepts in order to support and enhance students' learning of topics that are inherently complex and challenging. For example, an instructor following a more reductionist approach might use the NO_2 dimerization demonstration to support students' learning[42] of the challenging,[43] but core, concept of chemical equilibrium[44] and to provide a concrete reference for a future discussion of the effects of perturbations on a system at equilibrium.

Another teaching approach might be to provide some real-world context for the same demonstration. For example, an instructor might relate to students that the reddish-brown gas NO_2 is a component of the photochemical smog that contributes to the brown haze that is sometimes seen over large cities. The instructor might even go further to (1) place this information in context and (2) connect NO_2 to additional chemical content by discussing the relationship between NO_2 formation and the combustion of fossil fuels in automobiles. The lesson might be extended through the completion of a laboratory activity that gives the students concrete reference points for either photochemical smog or combustion of fossil fuels. Such a context-based approach has been shown to support student learning[45,46] and to increase student motivation to study chemistry because it connects chemical principles and concepts to familiar observations and experiences from the students' daily lives, making chemistry more relevant and interesting.[46−49]

A systems thinking approach would ask students to consider NO_2 and photochemical smog from yet another perspective: one that focuses not just on chemical context, but on dynamic behavior of chemicals; the causes of dynamic behavior; feedback systems; and social, environmental, and economic contexts. For example, perhaps after showing students the dimerization demonstration and telling students that NO_2 contributes to the photochemical smog over large cities, an instructor using a systems thinking approach might ask their students to consider how concentrations of NO_2 over a large city change over the course of a day [*dynamic behavior*]. When students discover that NO_2 concentration increases in the first part of the day and then decreases in the last part of each day [*a cyclic behavior*], the instructor might ask the students to think about variables that could increase the amount of NO_2, as well as variables that might decrease the amount of NO_2 [*causation*], such as the amount of NO released from the combustion of fossil fuels by automobiles (increase in NO_2) and the amount of sunlight (decrease in NO_2). The students might then be given an opportunity to develop a model of the interrelationships between processes that increase NO_2 and processes that decrease NO_2 [*organizing and quantifying relationships*].

Having established some of the chemical interactions that influence the formation and decomposition of the NO_2 component of photochemical smog, students might then be asked to consider how the amount of NO_2 could affect human actions and, in turn, how those actions might affect the amount of NO_2 [*feedback, interaction between a system and its environment*]. For example, NO_2 participates in other reactions, and the products of some of these reactions are irritating to the eyes and lungs. Students might suggest that the more NO_2 there is, the less people will want to be outside and, potentially, fewer people will walk to work. With fewer people walking to work, more people are driving to work, and the greater the future build-up of NO_2.

This example follows a systems thinking approach and also provides opportunities for contextually relevant discussions of key General Chemistry topics, such as reaction rates, equilibrium, thermodynamics, and combustion. It also provides a chance for students to consider how chemical reactions affect and are affected by human actions. An instructor could make the individual components of the example as teacher- or student-directed as they need to meet the constraints imposed by class time or class size. The example could also be further extended by asking students to consider the effects of NO_2 concentration on the health of those living in large cities, the economic costs associated with those health concerns, social justice issues related to the presence of the NO_2 in large cities (i.e., NO_2 and products of its reactions may have more of an effect on those who cannot afford to move outside of the city), and actions that can be taken to reduce the amounts of NO_2 in large cities [*democratic participation and ethical action*]. Overall, a systems thinking approach, as the example presented here, goes beyond just laying an environmental context over an equilibrium example. It allows an instructor to cover important chemistry concepts in a relevant context while *also* focusing on the causes and time-dependent character of a phenomenon and taking into consideration some of the social, environmental, and economic consequences of the phenomenon: real-world chemistry!

OPERATIONAL DEFINITIONS OF *SYSTEMS* AND *SYSTEMS THINKING*

Since the initial founding of the International Society for the Systems Sciences, systems approaches have continued to develop and mature in many different fields.[33] Each field has a slightly different conception of what a system is, and of what systems thinking is. For the purposes of the Systems Thinking in Chemistry Education (STICE) project and this paper, we focus on the most common aspects of the various conceptions of *systems* and *systems thinking*. Here, we present operational definitions of these two terms in order to provide common ground from which to discuss how systems thinking might be applied to chemistry education.

Systems thinking employs a variety of tools and cognitive frameworks to enhance our understanding of complex behaviors and phenomena within and between systems, both natural and artificial, from a holistic perspective. Systems thinking enables one to see higher-level behaviors and phenomena that one may not have predicted to arise out of a mere sum of the component parts of a system.

Systems exist at multiple scales, including microscopic, mesoscopic, and macroscopic, with the boundary conditions for a given system being established by its observer. Each system has at least three key characteristics: (1) components/parts, (2) interconnections between the components, and (3) a purpose.[2] Kim identified the following "defining" characteristics of systems (ref 39, p 3):

- Systems have purpose.[50]

DOI: 10.1021/acs.jchemed.9b00169
J. Chem. Educ. 2019, 96, 2720−2729

- All parts must be present for a system to carry out its purpose optimally.
- The order in which the parts are arranged affects the performance of a system.
- Systems attempt to maintain stability through feedback.

Systems thinking is "the ability to understand and interpret complex systems" (ref 8, p 655) and involves the following:

- visualizing the interconnections and relationships between the parts in the system;
- examining behavior that changes over time; and
- examining how systems-level phenomena emerge from interactions between the system's parts.

■ SYSTEMS THINKING SKILLS AND COMPETENCIES

Systems thinking can be further explained through an examination of the unique skills and competencies demonstrated by a systems thinker. While there are multiple lists of systems thinking skills in the literature, there is no consensus about which systems thinking skills students should develop and, to date, no chemistry-specific list of systems thinking skills.[2,4,51] In this section, we have chosen to focus our discussion on three different perspectives of systems thinking skills, each of which makes a unique contribution to an understanding of systems thinking and each of which could potentially inform the future development of a list of chemistry-specific systems thinking skills and competencies.

Richmond's Seven Systems Thinking Skills

Barry Richmond was an early systems scientist and one of the first systems thinking experts to describe specific skills that are typically involved in systems thinking.[19,52] Although Richmond's systems thinking skills were originally employed in the context of complex systems in business and management, Richmond noted that these skills could also be used to address growing interdependent global issues, such as ozone depletion, hunger, and poverty.[19] Much of the research about the use of systems thinking in educational contexts refers to Richmond's seven skills, and as a consequence, it is important to consider how they might be applied in a chemistry education context. A brief explanation of each of Richmond's systems thinking skills is presented below. Table 1 provides descriptions of ways that chemistry students might engage in each of these skills, with a primary focus on General Chemistry-relevant examples.

Dynamic Thinking. Typically, a reductionist approach focuses on events that occur at a given point in time. Dynamic thinking, on the other hand, involves looking at how behavior changes over time in order to develop an understanding of the factors that have influenced behavior in the past so that a change can be made to appropriately influence a behavior in the future.[53]

System-as-Cause Thinking. "System-as-cause thinking [...] is the notion that it is useful to view the structure of a system as the cause of the problem behaviors it is experiencing rather than seeing these behaviors as being foisted upon the system by outside agents" (ref 54, p 140). System-as-Cause Thinking encourages a learner to move away from a "blame the behavior on some outside, uncontrollable force" perspective to a "I can influence the behavior by changing a variable within my system" perspective (i.e., it allows the learner to recognize that they have power to generate a change in the system).[10]

Forest Thinking. Forest thinking is an invitation to examine the behavior of a system as a whole instead of focusing only on the parts of the system (a "tree-by-tree" thinking model).

Operational Thinking. Operational thinking focuses on the *causes* of a system's behavior and not on variables that are correlated with the behavior. Operational thinking also emphasizes *how* variables cause a given behavior.

Closed-Loop Thinking. Much of the reasoning currently employed in science education, and, to some extent, science research could be considered "straight line thinking" in which the direct effect of one variable on another variable is examined.[52] Closed-loop thinking takes into account the fact that, for example, while variable 1 might affect variable 2, variable 2 also affects variable 1. A familiar example of closed-loop thinking from a biochemistry context would be that of metabolic feedback loops. Figure 1 is causal loop diagram that shows potential effects of different variables on student exam performance and, in turn, how student exam performance influences those variables. The diagram is read in the directions indicated by the arrows. For example, student exam performance affects student course satisfaction, which then affects the amount of time students spend studying. The plus and minus signs in the diagram reflect the "polarity" of the cause-and-effect relationship. A plus (+) sign indicates that an increase in the first variable will also cause an increase in the second variable. A negative (−) sign indicates that an increase in the first variable will cause a decrease in the second variable. [Causal loop diagrams are further described in ref 55, in this same issue.]

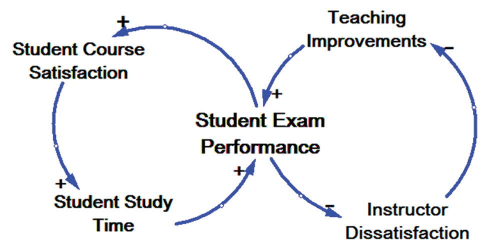


Figure 1. Causal loop diagram showing the interrelationships between student exam performance, student course satisfaction, student study time, instructor dissatisfaction, and teaching improvements.

Quantitative Thinking. Richmond suggests that, while not all variables can be measured, they can be quantified, in that someone can assign, on a relative scale, values to them.[52] The example Richmond uses is that you could say that complete commitment to a project could be represented by the number 100, while no commitment could be represented by a 0. Systems thinkers not only identify interrelationships between the parts of a system but also quantify the interrelationships and their contributions to an observed system behavior.

Scientific Thinking. Systems thinkers develop models to describe the interrelationships between parts of a system and how those parts contribute to a specific system-level behavior. They then make hypotheses based on those models. Scientific thinking involves the rigorous testing of developed models and hypotheses through either virtual or physical experimentation.[52]

While Table 1 provides applications of individual systems thinking skills, it is important to remember that a true systems thinking approach involves engaging students with *many* of these different ways of thinking over *multiple* contexts and concepts.

DOI: 10.1021/acs.jchemed.9b00169
J. Chem. Educ. 2019, 96, 2720−2729

Table 1. Chemistry-Relevant Applications of Richmond's Systems Thinking Skills

Systems Thinking Skill[a]	Description of Skill	Chemistry-Relevant Application of Skill
Dynamic Thinking	Examining how the behavior of a system changes over time	General Chemistry students engage in dynamic thinking when they examine how the concentrations of reactants change as a function of time as a reaction approaches equilibrium.
System-as-Cause Thinking	Considering the internal causes of a system's behavior, as opposed to potential external causes of the system's behavior	The self-assembly of random parts into an organized whole seems somewhat magical, leading some to believe that an external force causes the particles to assemble in an ordered way. Students who engage in system-as-cause thinking consider the weak interactions between the parts of the system and the interactions between the parts of the system and their environment as the cause for self-assembly.
Forest Thinking	Examining the behavior of a system as a whole, as opposed to the behaviors of the parts of a system	In many General Chemistry classes, students are given a list of rules by which to judge the solubility of ionic compounds in water. However, a consideration of the system as a whole would include not only the characteristics of the ionic compounds, but the characteristics of the water (the "environment") and the interactions between the ionic compounds and their environment, as well. Students engage in forest thinking when they consider not just a compound or a reaction, but how the environment surrounding that compound or reaction might influence its behavior.
Operational Thinking	Focusing on the variables that cause a system's behavior and how the variables cause a change in the system's behavior	Operational thinking is closely tied to system-as-cause thinking and involves identifying how a system really works. For example, a General Chemistry student might be able to state that adding more reactant will increase the rate of a chemical reaction without being able to explain how and why an increase in reactant concentration results in a faster reaction. Students engage in operational thinking when they use scientific theories (such as collision theory) to explain how a variable causes a change in a system behavior.
Closed-Loop Thinking	Considering the ways in which two system-relevant variables affect each other, as opposed to how one variable affects the other	The first step of glucose metabolism is catalyzed by the enzyme hexokinase. One of the end products of glucose metabolism is ATP. High levels of ATP, in turn, inhibit hexokinase. Students engage in closed-loop thinking when they consider the effects of this feedback loop on the future production of ATP from glucose metabolism.
Quantitative Thinking	Examining the relative impacts of variables on a given system behavior, as opposed to the absolute impacts of those variables	Many General Chemistry students memorize an algorithm for determining the direction a reaction will shift in response to a stress or perturbation. Students who engage in quantitative reasoning would consider how a particular stress changes the relative rates of forward and reverse reactions in order to determine the direction in which a reaction will shift.
Scientific Thinking	Testing of models and hypotheses about a system's behavior	Students who have learned about the kinetic molecular theory and about the behavior of individual gas particles can make predictions about the properties of large groups of gas molecules under different sets of circumstances (i.e., how the volume of the gas will change with increased pressure). Students engage in scientific thinking when they test their predictions on computerized simulations.

[a]See ref 52.

DOI: 10.1021/acs.jchemed.9b00169
J. Chem. Educ. 2019, 96, 2720−2729

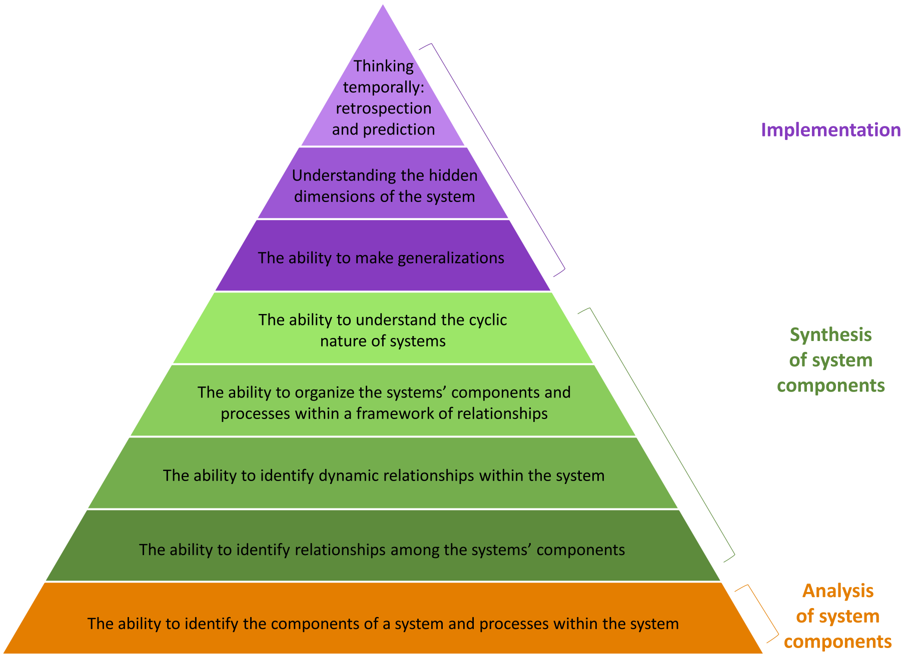


Figure 2. Systems Thinking Hierarchical Model pyramid.

Systems Thinking Hierarchical Model

Although Richmond's was one of the first lists of systems thinking, it has some limitations when one considers which systems thinking skills might be appropriate in the context of chemistry education. First, Richmond's systems thinking skills were not originally meant to be applied in a science education context. Second, the skills were not empirically derived. The Systems Thinking Hierarchical Model addresses both of these limitations.

Assaraf and Orion examined the systems thinking abilities of junior high school earth science students as they participated in a lesson about water cycles.[56] The lesson required students to consider (1) how various environmental phenomena interact with and contribute to water cycles and (2) how humans interact with water cycles.[57] Assaraf and Orion's data indicated that students engaged in eight distinct systems thinking skills, many of which align with Richmond's systems thinking skills. They also found that the eight systems thinking skills were developed in a hierarchical and sequential manner, meaning that achievement of lower-level skills was necessary (although not sufficient) for a student to advance to a higher-level skill. Assaraf and Orion named their ordered list of skills the "Systems Thinking Hierarchical Model" ("STH Model").[57] In Figure 2, we present our visual interpretation of their model.

In the STH Model, the eight systems thinking skills are divided into three "levels": (1) analysis of system components, (2) synthesis of system components, and (3) implementation.[56,57] From the bottom of the model, the first level, *analysis of system components*, includes only the first systems thinking skill: the ability to identify the components of a system and processes within the system. *Synthesis of system components*, the second level, encompasses systems thinking skills 2−5: the ability to identify relationships among the systems' components, the ability to identify dynamic relationships within the system, the ability to organize the systems' components and processes within a framework of relationships, and the ability to understand the cyclic nature of systems. Topping the pyramid is the third level, *implementation*, which includes the final three systems thinking skills: the ability to make generalizations, understanding the hidden dimensions of the systems, and thinking temporally: retrospection and prediction. Table 2 presents chemistry-relevant applications of each of the skills presented in the STH model, with reference to the NO_2 example presented in the Characteristics of Systems Thinking Approaches section.

From a chemistry education perspective, it is worth noting that the STH Model includes "understanding the hidden dimensions of the system" as one of the higher-level systems thinking skills.[56,57] Assaraf and Orion found that the junior high school earth science students struggled to "see" and recognize parts and processes of a system that are hidden, such as microlevel objects and processes (i.e., water molecules), physically hidden or invisible processes (i.e., those involving gases), or large scale processes (i.e., on the level of populations). As chemistry involves many "hidden" parts and processes, it is important to consider how to best help students access and consider these hidden dimensions when they engage in systems thinking.

Systems Thinking Core Competency in Public Health

Finally, we briefly present systems thinking skills from the field of public health (Box 1), where they are considered part of a "Core Competency".[58,59] Although many of these skills mirror those found in Richmond's list or in the STH Model, others are unique in that they emphasize the effects of human actions on various systems, an essential focus not included in many lists of systems thinking skills.[59] For chemists to effectively address global challenges like sustainability, pollution, climate change, and poverty, they will need to acknowledge not only how others' actions influence the chemistry they do, but the implications of their own decisions and actions on various political, social, economic, and environmental systems—at local, national, and international scales. Accordingly, we believe that any attempt to integrate systems thinking into chemistry education should include an explicit consideration of the effects of human choices

DOI: 10.1021/acs.jchemed.9b00169
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Table 2. Chemistry-Relevant Applications of Skills from the Systems Thinking Hierarchy Model

Skill from the STH Model[a]	Question that Engages Students in STH Skill	Chemistry-Relevant Application of Skill[b]
Ability to identify the components of a system and processes within the system	What are the components of the system and what are their characteristics?	In order to understand the NO_2/photochemical smog system, students first need to identify and understand components and processes that affect the amount of NO_2, including, for example, the amount of NO released by combustion of fossil fuels, the amount of sunlight, and human actions.
Ability to identify relationships among the system's components	Which components of the system are related or connected?	A next step in understanding the NO_2/photochemical smog system might be to examine the characteristics of the chemical reactions by which NO is converted into NO_2 and/or the photochemical decomposition of NO_2.
Ability to identify dynamic relationships within the system	How are the components of the system related? How do the components affect each other as a function of time?	Having identified that the amount of NO_2 increases with the amount of NO and decreases with the amount of sunlight, students might then examine the rates of these two reactions.
Ability to organize the systems' components and processes within a framework of relationships	How are all of the relationships within a system interconnected?	Knowing about the rates at which NO_2 is produced from NO and at which NO_2 is photochemically decomposed, students can consider the relative rates of these two reactions and how the two processes, together, might affect the concentrations of NO_2.
Ability to understand the cyclic nature of systems	What are some of the repeating patterns in the behavior of the system? What might be causing those repeating/cycling behaviors?	If students observe and measure NO_2 concentrations over the course of a day, they will notice that the system exhibits a cyclic behavior: NO_2 concentrations increase each morning and decrease each evening. The students may be able to use their knowledge of the relationships between the systems' components to explain this cyclic behavior.
Ability to make generalizations	What are some of the general patterns in this system that might apply to other systems?	Noticing that some system processes increase NO_2 concentrations while other system processes decrease NO_2 concentrations, students may be able to generalize that there are processes that increase the amounts of other atmospheric gases, like ozone, *and* processes that decrease the amounts of these gases.
Understanding the hidden dimensions of the system	What invisible components and processes might be contributing to the system's behavior?	Chemistry systems are often challenging for students to understand because they involve many "invisible" components and processes. It is important for students to understand how these components and processes they cannot see—like individual gas molecules—can contribute to a macroscopic property that they can see—photochemical smog.
Thinking temporally: retrospection and prediction	How have past actions affected the current behavior of the system? How might current actions affect the future behavior of the system?	This skill involves the ability to recognize that the current behavior of a system is influenced by what has happened in the past and that current actions will influence the future behavior of the system. For example, concentrations of NO_2 have varied in the past, increasing gradually over time. When students recognize factors that impact NO_2 concentrations, they can make predictions about the influence that a particular action will have on future air quality.

[a]See ref 57. [b]The applications included in this table are based on the very simplified NO_2/photochemical smog example presented in the Characteristics of Systems Thinking Approaches section.

DOI: 10.1021/acs.jchemed.9b00169
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Box 1. Systems Thinking Skills included in Public Health Core Competencies (Reprinted with permission from ref 59. Copyright 2008 American Public Health Association.)

Public Health Competencies in Systems Thinking

The ability to recognize system level properties that result from dynamic interactions among human and social systems and how they affect the relationships among individuals, groups, organizations, communities, and environments.

- Identify characteristics of a system.
- Identify unintended consequences produced by changes made to a public health system.
- Provide examples of feedback loops and "stocks and flows" within a public health system.
- Explain how systems (e.g., individuals, social networks, organizations, and communities) may be viewed as systems within systems in the analysis of public health problems.
- Explain how systems models can be tested and validated.
- Explain how the contexts of gender, race, poverty, history, migration, and culture are important in the design of interventions within public health systems.
- Illustrate how changes in public health systems (including input, processes, and output) can be measured.
- Analyze inter-relationships among systems that influence the quality of life of people in their communities.
- Analyze the effects of political, social, and economic policies on public health systems at the local, state, national and international levels.
- Analyze the impact of global trends and interdependencies on public health related problems and systems.
- Assess strengths and weaknesses of applying the systems approach to public health problems.

and actions on both chemical systems and on the larger systems in which chemistry plays a part, as has been done in the public health competencies in systems thinking.

SUMMARY

The current article has described the origins and characteristics of systems thinking. It has also introduced some of the skills typically engaged in by systems thinkers. Other articles in this special issue of the *Journal* will further describe the place of systems thinking in STEM education and green chemistry initiatives, as well as the role that systems thinking could play specifically in chemistry education. Overall, systems thinking can be a powerful complement to reductionist approaches to both chemistry and chemistry education. Systems thinking can help current chemists, future chemists, and future global citizens view chemistry not only as an object to be learned and studied, but as a useful tool for addressing some of the complex global challenges that we encounter today as a society.

Systems thinking, when used as a complement to reductionist approaches, could have a significant effect on how we do, teach, and learn chemistry. Consider the following, if chemists were to adopt more systems thinking approaches:

- How might chemistry, chemistry education, and chemists change?
- What new chemistry might be discovered?
- What new methods might be developed?
- What new applications might we see for chemistry in solving the world's global challenges?
- How might we alter chemists' views of their responsibilities to the earth and its citizens?
- How might we change the way that students and society as a whole view the purpose and products of chemistry?

Given the positive outcomes of applying these approaches in other fields,[22] we believe it is worth examining how systems thinking can similarly transform both chemistry and chemistry education.

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Notes

The authors declare no competing financial interest.

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DOI: 10.1021/acs.jchemed.9b00169
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