Integrating the Molecular Basis of Sustainability into General Chemistry through Systems Thinking

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Abstract
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Keywords

Disciplines
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Comments
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Integrating the Molecular Basis of Sustainability into General Chemistry through Systems Thinking

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ABSTRACT: The flow of materials and energy through society is an integral but poorly visible element of global sustainability agendas such as the Planetary Boundaries Framework and the UN Sustainable Development Goals (UNSDG). Given that the primary activities of chemistry are to analyze, synthesize, and transform matter, the practice of chemistry has a great deal to contribute to sustainability science, which in turn should play an increasingly important role in reshaping the practice of chemistry. Success in integrating sustainability considerations into the practice of chemistry implies a substantial role for chemistry education to better equip students to address the sustainability of earth and societal systems. Building on the framework of the IUPAC Systems Thinking in Chemistry Education (STICE) project, we develop approaches to using systems thinking to educate students about the molecular basis of sustainability, to assist chemistry to contribute meaningfully and visibly toward the attainment of global sustainability agendas. A detailed exemplar shows how ubiquitous coverage in general chemistry courses of the Haber–Bosch process for the synthesis of ammonia could be extended using systems thinking to consider the complex interplay of this industrial process with scientific, societal, and environmental systems. Systems thinking tools such as systems thinking concept map extension (SOCME) visualizations assist in highlighting inputs, outputs, and societal consequences of this large-scale industrial process, including both intended and unintended alterations to the planetary cycle of nitrogenous compounds. Strategies for using systems thinking in chemistry education and addressing the challenges its use may bring to educators and students are discussed, and suggestions are offered for general chemistry instructors using systems thinking to educate about the molecular basis of sustainability.


INTRODUCTION

We begin by unpacking two key terms from our title that may be relatively unfamiliar to many chemistry educators.

Systems thinking moves chemistry education beyond reductionist approaches that provide fragmented knowledge of chemical reactions and processes to a more holistic understanding of how knowledge of chemistry connects to the dynamic, complex social, technological, economic, and environmental systems at work in our world. The emerging area of systems thinking in chemistry education (STICE) uses tools, strategies, and cognitive frameworks to visualize interconnections and relationships among parts of a system, to examine how the behavior of the system changes over time, and to understand how systems-level phenomena emerge from interactions among the systems parts.† The STICE framework, formulated by an international IUPAC project,‡ has the goal of articulating strategies and exemplars for infusing systems thinking into chemistry education, with a focus on postsecondary first-year or general chemistry. The STICE framework places the learner in the center of a system of learning, with three interconnected nodes or subsystems (Figure 1). In this representation we use gears or cogwheels as a visual metaphor for the three nodes, emphasizing the dynamic interconnection of the nodes as a part of a system of learning, and the influence that the activity of each element of learning has on the others. The Educational Research &

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Theories node explores and describes the processes at work for students, including the following: learning theories, learning progressions, cognitive and affective aspects of learning, and social contexts for learning. The Chemistry Teaching & Learning node applies general understanding of how students learn to the unique challenges of learning chemistry. These include the use of pedagogical content knowledge; analysis of how intended curriculum is enacted, assessed, learned, and applied; and incorporation of student learning outcomes that include responsibility for the safe and sustainable use of chemistry. The Earth & Societal Systems node orients chemistry education toward meeting societal and environmental needs articulated in initiatives such as the UN Sustainable Development Goals and the Planetary Boundaries framework.

The molecular basis of sustainability is a term introduced by Anastas and Zimmerman in 2016 to emphasize that many environmental concerns are derived from molecular considerations, and that solutions must also feature molecular dimensions. We have expanded on their use of the term to define the molecular basis of sustainability as “the ways in which the material basis of society and economy underlie considerations of how present and future generations can live within the limits of the natural world”\(^{4}\). This definition reflects the central role for chemistry in analyzing, synthesizing, and transforming matter (essential to all aspects of society) and establishes the need for both the practice of chemistry and education in and about chemistry to address the sustainability of earth and societal systems.

As one outcome from deliberations by the IUPAC Project on STICE\(^2\) which has led to this special issue of the Journal on systems thinking and its connections to green and sustainable chemistry,\(^3\) we recommend that chemistry educators use, where appropriate, a systems thinking framework to develop a central guiding theme of the molecular basis of sustainability, so as to reorient chemistry education to better equip students to address the multiple global challenges emerging in the anthropocene epoch.

To develop a better understanding of the compelling need for an orientation by the chemistry profession toward the molecular basis of sustainability, we trace in this paper the evolution of sustainability concepts and agendas leading to the emergence of sustainability science and draw out the existing and potential interconnections with chemistry and chemistry education. We discuss the central premise that, to enhance chemistry’s overall contribution to tackling sustainability challenges, chemistry education needs to help learners use systems thinking to see the interconnections both among branches within the discipline itself and between chemistry and other disciplines and domains within and outside of the natural sciences. Of particular importance is the interplay between chemistry and earth and societal systems.

We illustrate some ways in which systems thinking might apply to a central topic in chemistry education, considering what students in general chemistry currently learn about...
ammonia and the planetary reactive nitrogen cycle, and suggesting ways in which a systems thinking lens can help orient that learning toward the molecular basis of sustainability. In current educational practice, the Haber−Bosch reaction is usually presented as an isolated example in a unit on equilibrium. We illustrate some ways in which systems thinking can equip instructors to zoom out from a narrow consideration of the reaction to a more integrated approach to teaching about reactive nitrogen species, highlighting the ways that important compounds of nitrogen participate in intended ways in societal and economic systems, the resultant unintended impacts of biogeochemical flows of nitrogen on planetary systems, and the deeply embedded, but poorly visible, linkages to sustainability agendas.

Systems-oriented concept maps (SOCMEs) are introduced in the reactive nitrogen example to help educators and students visualize how the core Haber−Bosch reaction is interconnected with other subsystems such as the chemical and energy inputs, the reaction conditions, the products arising from the Ostwald process, and the intended and unintended uses of those products, with consequences for society. Teaching complexity is an inherent challenge built into the study of systems and their interactions. Systems thinking provides tools to manage this complexity, including SOCME visualizations to select boundaries around those subsystems that are congruent with student learning outcomes for a particular course or topic within a course.

We conclude with suggestions for general chemistry instructors wishing to use systems thinking to orient teaching and learning toward the molecular basis of sustainability.

### CHEMISTRY, HUMAN DEVELOPMENT, AND GLOBAL SUSTAINABILITY AGENDAS

From its earliest days, chemistry has made major contributions to innovations in diverse fields including agriculture, industry, medicine, energy, transport, and overall economic growth. However, the practice of chemistry and other components of science, technology, and innovation (STI) has not always had benign impacts on human beings or the biological or physical environments of the planet. Analysis of the environmental footprint caused by the rapid acceleration of human activity from the 1950s to the present day, referred to as “the great acceleration,” has led to recommendations by the professional community of geological scientists that the Holocene epoch (a geological period of 12,000 years of remarkable stability in the planetary climate) should now be considered to have been supplanted by the Anthropocene epoch. This period is characterized by challenges arising from the dominant role of overall human activity in shaping the planetary environment, including accelerated rates of carbon dioxide emissions and sea level rise, the global mass extinction of species, unsustainable increases in the flow of reactive nitrogen and phosphorus, and the transformation of land by deforestation and development.

Over the past several decades, a variety of agendas have emerged that attempt to focus attention and action on ways to reduce and mitigate the rapidly emerging adverse anthropogenic impacts at local and global levels. Sustainable development is now an overarching priority for many governments, intergovernmental agencies such as the United Nations, corporations, research laboratories, and universities.
While these agendas are all policy-oriented, they require fundamental inputs from STI at every stage, from recognizing and defining the problem, to establishing means of detection, monitoring key indicators, and presenting viable solutions on a variety of time scales.

Over the past 20 years, work across disciplines to address those sustainability agendas has created an increasingly structured scientific field of sustainability, which is establishing a theoretical base and is beginning to integrate perspectives across the social and natural sciences, engineering, applied science, and policy.11

Two high profile global sustainability frameworks informed by sustainability science that draw strongly on the molecular basis of sustainability are the Planetary Boundaries Framework and the UN Sustainable Development Goals. Their grounding in the molecular sciences is not particularly visible, nor has the profession of chemistry been quick to embrace its central role in achieving sustainable development agendas.12 Using systems thinking to draw out the interconnections among core chemistry content and the various features of these two frameworks provides an opportunity for chemistry educators to engage students in current efforts to explore fundamental inputs from STI at every stage, from recognizing and defining the problem, to establishing means of detection, monitoring key indicators, and presenting viable solutions on a variety of time scales.

The Planetary Boundaries Framework (Figure 2), presented by Rockström, Steffen, and colleagues in 200913 with a substantial update in 2015,14 a quantitative assessment of nine earth system processes of critical relevance for sustainable development has been carried out. For six of the earth systems, control variables have been identified and analyzed quantitatively. Progression from the center toward the outside of the figure within each earth system is plotted by the numerical value of that control variable. The threshold for each earth system, represented by the outer of two gray circles on the figure, represents a tipping point or region of high risk that would represent a large-scale abrupt or irreversible environmental change for that earth system. The planetary boundary is the gray circle closer to the center of the figure, which represents for each earth system the value of the control variable that maintains a safe operating space relative to the threshold.

For example, Figure 2 shows that the control variable for the planetary boundary established for the biogeochemical cycles of reactive nitrogen are presented later in this paper.

One example of successful engagement by the chemistry profession in systems thinking to prevent movement of a control variable beyond a planetary boundary is the stratospheric ozone earth system, one of the nine earth system processes in this framework. Following the demonstration that the photolysis of atmospheric CFCs by sunlight releases chlorine atoms which act as catalysts to break down stratospheric ozone,15 the Montreal Protocol on Substances that Deplete the Ozone Layer16 was signed in 1987. Richard Benedick, who headed the US delegation in the ozone negotiations, commented17 that there was a need “to bridge traditional scientific disciplines and examine the earth as an interrelated system of physical, chemical, and biological processes”.

This use of systems thinking led to global action that brought the control variable for stratospheric ozone depletion back below the planetary boundary, a hopeful precedent for tackling other boundaries. However, the limits to the application of systems thinking are also apparent 30 years after the Montreal Protocol was signed. Short-term (HCFCs) and longer-term (HFCs) replacement compounds for CFCs have significantly addressed the release of chlorine atoms into the stratosphere, but the global warming potential of these replacement compounds was not fully considered at the time of implementation. Many of the HFCs have ozone depletion potentials of zero but global warming potentials that are hundreds or thousands of times that of CO₂.

The planetary boundaries concept fed into the formulation of the UN Sustainable Development Goals (SDGs).18

The central importance of the chemical sciences to achieving sustainability agendas is evident in considering the material basis of society, and in recognizing the central role for the practice of chemistry, as a result of the profession’s primary activities of analyzing, synthesizing, and transforming matter. The flow of reactive nitrogenous compounds is one profound way in which the earth systems in the planetary boundaries framework and the 17 goals of the UNSDGs are interconnected. This is illustrated later in discussing the flow of reactive nitrogenous compounds.

The profession of chemistry has responded to its role in achieving sustainability agendas in a variety of ways, including the following:

- The evolution of environmental chemistry as a multidisciplinary science. From the 1960s, there was increasing legislation and regulatory action on pollution.
By the 1990s, policy approaches were refocused from pollution control to pollution prevention.

- The development of green chemistry principles and practices. This represents a shift toward the active prevention of pollution through design.25
- The application of life cycle assessment (LCA). LCA considers all steps from the acquisition of raw materials to the disposal or recycling of waste- and end-products.26 It brings together green chemistry approaches and knowledge of toxicology, environmental dispersal and degradation routes, and ecology of the relevant surroundings, creating an overall picture of the likely energy and material inputs and environmental releases, facilitating comparison of alternatives for products and processes. LCA also links with the 3R Initiative, (Reduce, Reuse, and Recycle).27 “cradle-to-cradle” design,28 and the application of circular economy concepts29 to define the emerging field of circular chemistry, which emphasizes “the role of chemists in a world without waste” and has advanced a set of 12 principles to guide its application.30−32 The circular economy seeks to move a traditional linear economy (make, use, dispose of products) to one in which we keep resources in use for as long as possible, extract the maximum value from them while in use, and then recover and regenerate products and materials at the end of each service life.33
- The development by the International Organization for Chemical Sciences in Development (IOCD) of the concept of “one-world chemistry”.34 This seeks to reposition chemistry as a sustainability science for the benefit of society, recognizing that the healths of human beings, animals, and the environment are interconnected and require the adoption of systems thinking and cross-disciplinary working.

Despite these important signs of chemistry’s increasing engagement with the challenges of sustainability, the discipline of chemistry is not yet visibly well-represented in the rapidly emerging field of sustainability science,11 and reorienting chemistry education to better address the sustainability of earth and societal systems is needed. Using systems thinking to guide efforts to educate about the molecular basis of sustainability (Figure 4) provides one avenue to more fully orient chemistry education and chemistry practice toward sustainability. Recent literature suggests that systems thinking can be valuable in increasing understanding of complex environmental challenges such as global climate change.35

### USING SYSTEMS THINKING TO EDUCATE ABOUT THE MOLECULAR BASIS OF SUSTAINABILITY: AN EXEMPLAR BASED ON PLANETARY CYCLES OF REACTIVE NITROGEN

Gateway general chemistry courses, such as advanced-level high school chemistry courses in some European countries and first-year postsecondary general chemistry courses in North America and some other countries, could play a central role in educating about the molecular basis of sustainability, as they are populated both by future chemists and by a large majority of students who will embark on a wide range of STEM careers that require some fundamental knowledge of chemistry. However, to do so, they will require reorientation.

Analyzing general chemistry coverage of the Haber−Bosch process, we illustrate current practice and some ways in which systems thinking might provide that reorientation to help chemistry education better address the sustainability of earth and societal systems.

\[
\text{N}_2(g) + 3\text{H}_2(g) \xrightarrow{\text{catalyst}} \text{N}_3\text{H}_6(g)
\]

The Haber−Bosch process receives mention in virtually all general chemistry textbooks. However, typical coverage of this reaction, which plays a central role in planetary cycles of reactive nitrogen compounds, reflects the presentation of chemical reactions and processes as isolated facts intended to demonstrate aspects of descriptive chemistry, fundamental concepts, principles, or mathematical calculations. An informal survey of representative textbooks shows that most often the reaction is introduced in a unit or chapter on thermochemistry, often followed by mathematical or conceptual questions related to equilibrium calculations. The importance of the catalyst is sometimes mentioned in a chapter or unit on kinetics. A picture or sidebar on Fritz Haber might be included along with a caption referring to his receipt of a Nobel Prize in Chemistry. Any coverage of the compounds derived from ammonia, if their origin is mentioned at all, might be found in a chapter on descriptive chemistry of main group elements.

Systems thinking provides a framework and tools to help general chemistry educators explore how to connect this chemical reaction to planetary cycles of nitrogenous compounds, and to weave the coverage of core chemistry concepts into discussion of sustainability agendas such as the planetary boundaries framework and the UNSDGs. Expanding the boundaries of the usual presentation of this reaction gives students an introduction to the application of systems thinking and a good example of the meaning and importance of the molecular basis of sustainability.

Elemental nitrogen, \(\text{N}_2\), comprises 78% of the gaseous composition of air, and yet that atmospherically abundant species is too unreactive to be directly utilized by most organisms to produce the nitrogenous compounds that make nitrogen the fourth most abundant element of cellular biomass.36 It was recognized a century and a half ago that plant growth is limited by the availability of reactive or fixed nitrogen. In 1898, Sir William Crooks, observing that new sources of fixed nitrogen to replace Chilean saltpeter were needed to stave off mass starvation, issued a call to chemists to “come to the rescue” of threatened European communities and use their “genius” to find ways to produce reactive and bioavailable nitrogenous compounds on a global and industrial scale.37 Chemist Fritz Haber successfully answered that call, filing his patent on “the synthesis of ammonia from its elements” in 1908, and engineer Carl Bosch scaled up this reaction to an industrial scale. Haber received the Nobel Prize in 1918 and Bosch in 1931. The award to Haber was subsequently heavily criticized, as he had developed chemical weapons used by the German army during World War I.

What important and motivating interconnections to the molecular basis of sustainability might be drawn out for students by zooming out from a narrow consideration of the reactants and products and equilibrium conditions of this industrial process to consider some of the systems to which the reaction connects?38 In the century since Haber’s Nobel Prize, the scale of anthropogenic nitrogen fixation has grown to 210 Tg yr\(^{-1}\), requiring almost 2% of global fossil fuel consumption.
It is estimated that over 40% of the current human population would not be here without food grown with nitrogen-based fertilizers derived from the Haber−Bosch process. Yet a systems analysis using principles of green chemistry shows that more than half of the N applied to agricultural land in the form of fertilizers does not go to its intended use to provide the molecular building blocks for plant and animal growth. Also, to meet global food demand, crop production needs to increase by ∼60−100% from 2007 to 2050, placing large additional demands on the production of fixed nitrogen.
Ammonia also plays a central role in the manufacture of polymers such as nylon, as well as explosives and munitions: the Haber–Bosch process can be linked to 100–150 million deaths in armed conflicts in the 20th century.40 Beyond the intended consequences of ammonia production, leading to the many products derived from ammonia directly or from urea, nitric acid, and ammonium nitrate, the overproduction of reactive nitrogen from the Haber–Bosch process and NO$_x$ production from fossil fuel combustion have led to serious ecosystem disturbances. These include eutrophication of water, soil acidification, the formation of secondary atmospheric particulate matter, and the release of the potent greenhouse gas nitrous oxide from soil ecosystems as a result of nitrification and denitrification processes following nitrogen fertilization, manure management, and biomass burning. For example, maize production in the US alone is estimated to cause 4,300 premature deaths per year as a result of the secondary production of PM$_{2.5}$ aerosols from ammonia, NO$_x$, SO$_x$, and VOCs.41

Figure 6. An alternative system-oriented concept map extension for the Haber–Bosch reaction, emphasizing the distinction between the renewable and nonrenewable natural resources subsystems needed to produce the N$_2$ and H$_2$ reactants, and highlighting the link to global food security.

We have created two alternative systems-oriented concept map extensions (SOCMEs)$^{4,6}$ to visualize some of the relevant systems at work by zooming out from the simple Haber–Bosch reaction equation. Figure 5 introduces new nodes or subsystems beyond the core reaction system that focus on chemical inputs, energy inputs, reaction conditions, outputs such as the Ostwald process leading to ammonium nitrate, and the intended uses of nitrogenous compounds derived from ammonia in agriculture and munitions, as well as unintended consequences resulting from the overuse of reactive nitrogen.

The purpose of a SOCME visualization is to stimulate questions about how the chemical reaction or process (in this case) is connected to broader STI and earth and societal systems. Students might ask, “Is this reaction or process good for agriculture, for mining/construction, for the environment, for the wellbeing of the planet?” The choice of questions...
depends on the questioner’s interest in the purpose and function of the system. Moreover, they point the learner toward additional questions, such as “What boundary am I using for this concept?” and “Is this the correct boundary or are other, connected subsystems important to include?”

The choice of subsystems identified in a SOCME for focus in a particular first-year chemistry course can be determined by the learning outcomes for that course, established so as to meet the learning needs of the students who take it. To nurture systems thinking, it might be helpful to show students a widely expanded SOCME and then the selection of boundaries for their consideration to address those learning outcomes. Boundary selection would differ among general chemistry courses depending on student learning needs and motivations (e.g., students focusing on life sciences, health science careers, agriculture, materials science, engineering, chemistry majors, or a mix of all of these groups). The SOCME in Figure 5 could be expanded beyond what is shown to draw attention to alternative chemical inputs, such as those found in the electrochemical production of ammonia, and/or the critical materials needed for chemical and energy inputs.

Figure 6 presents an alternative SOCME with different emphases placed on several subsystems, with this one emphasizing the distinction between the renewable and nonrenewable natural resources subsystems needed to produce the N2 and H2 reactants. The societal subsystem highlights the link to global food security and conflict.

The Figure 5 and 6 SOCMEs provide good alternative entry points to consider how examination of core chemistry concepts, the molecular basis of sustainability, and the intended and unintended societal consequences resulting from the Haber−Bosch process can lead to the emergence of insights into how system of reactive nitrogen compounds can inform efforts to address many of the 17 UNSDGs (Figure 3) and the earth systems identified in the Planetary Boundaries Framework (Figure 2). An analysis of the role of nitrogenous compounds derived from the Haber−Bosch process in achieving the UNSDGs has been visualized and discussed.5

In the Planetary Boundaries Framework (Figure 2), the control variable for the planetary boundary established for the amount of industrial and intentional biological fixation of N is 62 Tg N yr−1. The current value of ∼150 Tg N yr−1 far exceeds both that planetary boundary and the threshold.14 Other earth systems in the Planetary Boundaries Framework directly and substantially affected by the overproduction of fixed nitrogen include the fresh water, climate change, land use, biodiversity, and stratospheric ozone depletion systems.

Building on the SOCMEs for reactive nitrogen in Figures 5 and 6, we offer several concrete examples of how instructors can implement systems thinking (ST) into chemistry classroom practice. Instructors can use a published set of student performance expectations to guide their development of additional activities and assessments related to the Haber−Bosch process.8 One example of how to do so, developed from consideration of interconnections between the reactive nitrogen SOCME in Figure 5 and the nitrogen planetary boundary, was implemented in a general chemistry course. Students in general chemistry routinely learn that all nitrates are soluble. The implications of this core chemistry concept for nitrate loading of rivers in agricultural areas can be readily emphasized. In a large midwestern university in the United States, systems-oriented teaching activities have been developed for a two-semester general chemistry course around the claim that 41% of the nitrates that arrive in the Gulf of Mexico are sourced from the state of Iowa.53 This exercise provides several key ways to enhance both systems and computational thinking, by asking students to identify large-scale boundaries as well as postulate mathematical models that can adjudicate the veracity of this claim. In so doing, a somewhat bland chemical fact about solubility becomes a source of connecting chemistry to real-world applications that importantly connects to the even larger planetary boundaries framework.13,14

Additional work is underway by the author team to develop learning outcomes and expectations based on the SOCME in Figure 6 to guide the development of resources for instructors wishing to expand the coverage of reactive nitrogen chemistry in three courses: general chemistry, environmental chemistry, and main group chemistry.

Finally, a teacher action research project in which a systems thinking approach was implemented into a 15 h Australian depth study for students in their final year of secondary chemistry, has been reported in this special issue.44 A systems diagram of the Haber−Bosch process was presented by a teacher to reinforce and illustrate concepts and tools of systems thinking, and the interconnection of fundamental chemistry concepts with sustainability agendas. Students then developed their own systems map to investigate the interrelationships between the syntheses of ethylene and ethanol, and the connections of this chemical system to global sustainability agendas.

Systems thinking can also help students explore ways in which new directions in chemistry at its societal interfaces can contribute toward solutions to sustainability challenges, such as the innovations needed to improve efficiencies in the production and use of nitrogenous compounds to ensure their sustainable role in food supply and security as well as in key environmental systems. New approaches such as biomimicry might be introduced, such as efforts by chemists to mimic nitrogenase enzymes in various nitrogen-fixing bacteria that carry out biological nitrogen fixation under ambient conditions rather than the very high temperature and pressure required for the Haber−Bosch process. Alternative energy sources to produce ammonia are under consideration, such as off-shore wind farms.35 The system under consideration might also include more emphasis on the function of ammonia and derived products, including a return to interest in the use of ammonia as a domestic refrigerant46 in light of the challenge of finding CFC replacement compounds that are not also potent greenhouse gases. Also, ammonia is being considered as a fuel in solid oxide fuel cells.47 The production of urea as a commodity chemical from ammonia is initially attractive from a sustainability perspective, as it captures carbon dioxide; however, following the application of urea as a fertilizer, some of that carbon dioxide is released back into the atmosphere, along with nitrous oxide. However, innovations use ammonia to capture CO2 from a power plant flue gas and regenerate both CO2 for carbon capture and storage or utilization, and ammonia which goes back into the scrubbing process.48 A survey of the sources and fates of industrial, natural, and agricultural products containing or derived from reactive nitrogen provides numerous additional systems to consider, with respect to products, function, and intended and unintended consequences.49
Using a systems thinking approach to expand the boundaries of reductionist coverage of the Haber–Bosch reaction to a more holistic approach introduces both opportunities and significant challenges for students who may have had little experience in analyzing and synthesizing system components or in seeing dynamic interconnections between isolated chemistry content and the flow of material and energy through earth and societal systems. To address the challenges of teaching from an ST framework, the IUPAC STICE project group has outlined future directions for the project, identifying the following as high priorities: (1) developing systems thinking resources for chemistry educators and students, (2) identifying chemistry education research needed to investigate and improve systems thinking approaches, and (3) investigating opportunities to apply chemistry-related systems thinking approaches in broader educational contexts.52

Drawing on insights gained from the work of the IUPAC STICE project, including the overall project recommendations for future directions, and generalizing from our development of the use of systems thinking to introduce planetary cycles of reactive nitrogen in this paper, we conclude by offering a set of suggestions for general chemistry instructors to facilitate their use of systems thinking to educate about the molecular basis of sustainability. These suggestions offer strategies and guidance to address challenges such as dealing with complexity that are inherent in expanding boundaries of reductionist presentation of chemistry content to include interconnections, dynamic behavior, and emergence that arise from consideration of broader systems. In our view, decisions to implement systems thinking approaches to incorporate the molecular basis of sustainability in general chemistry courses will be most successful if they are implemented in ways that reflect a true understanding of the institutional context, including program and curriculum standards, for the learners in the center of the instructional system (Figure 1).51 In some cases a large-scale transition to a new approach may be possible. In many other cases, incremental steps toward implementing systems thinking, congruent with both learning goals and available resources and informed by research emerging from future directions for the STICE project, may be more successful.

(1) Course-level learning outcomes (LOs) for general chemistry articulated though the lens of systems thinking, and aligned with curriculum, pedagogies, and assessments, can be an important step in developing learning environments in which students can “see the forest” and more integrally connect knowledge of chemistry to the dynamic, complex social, technological, economic, and environmental systems at work in our world.

(2) Since systems thinking approaches and tools are not yet widely implemented in chemistry education, training in systems thinking is needed for future teachers, as professional development for current chemistry educators, and for ST learning activities for students. Teaching and assessing the use of systems thinking tools and strategies might best be done by integrating their use with the introduction of chemistry content.7

(3) A systems thinking hierarchical model pyramid4 may help instructors visualize three general levels of systems thinking to shape curriculum design and select coherent pedagogies, (a) analysis of system components, (b) synthesis of system components, and (c) implementation, leading ultimately to the ability to make generalizations, to understand the hidden dimensions of systems, and to think temporally. Further work will be needed to refine this model, which was developed for geoscience education, to increase its relevance for chemistry education in general and to develop better understanding of the molecular basis of sustainability.

(4) Considerations from the Educational Research & Theories and Chemistry Teaching & Learning nodes of the STICE framework (Figure 1) can help instructors anticipate and address challenges in using systems thinking approaches. These include dealing with complexity, attending to cognitive load, and identifying student prior understanding of concepts integral to both chemistry content and to understand interconnections to earth and societal systems.

(5) System visualization tools, such as system-oriented concept map extension (SOCME) diagrams,6 can help instructors and students zoom out from a narrow consideration of a reaction or process to see some of the interconnections among isolated topics and other aspects of chemistry and their connections to other systems. The boundaries for how far and in which directions to zoom out can be set by course- and topic-level learning outcomes (LOs).

(6) In keeping with calls from industry and other stakeholders to incorporate sustainability principles throughout the chemistry curriculum,55 we suggest that demonstrating an understanding of the molecular basis of sustainability, that is, “the ways in which the material basis of society and economy underlie considerations of how present and future generations can live within the limits of the natural world”,4 might become a central learning outcome for general chemistry.

(7) In considering the primary activities of chemists, to analyze, characterize, and transform the material world, course- and topic-level LOs should illustrate that chemicals have both benefits and hazards, and that these should be considered together.50

(8) A systems view to introducing, where appropriate, content and approaches from environmental chemistry, green and sustainable chemistry, life cycle analysis, and circular chemistry can help to strengthen student understanding of the molecular basis of sustainability. A systems thinking framework can also help to infuse these approaches more integrally into core courses such as general and organic chemistry.

(9) To influence practice, external drivers, including external accreditation of chemistry programs, should include guidelines and motivation to introduce systems thinking approaches and sustainability considerations.

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