Reorienting chemistry education through systems thinking

Peter G. Mahaffy, Alain Krief, Henning Hopf, Goverdhan Mehta and Stephen A. Matlin

It is time for chemistry learning to be reoriented through systems thinking, which offers opportunities to better understand and stimulate students' learning of chemistry, such that they can address twenty-first century challenges.

In biology courses, it is difficult to imagine studying organisms, such as *Plasmodium* spp. parasites that cause malaria, without attending to their function as interdependent components of a web of biological and other systems. Those systems need to be understood at different levels — from molecular and cellular mechanisms, through the development and habitat of parasites and hosts (including the *Anopheles* mosquito), to the entire ecosystem that regulates their life cycle and ultimately the socio-economic and environmental parameters that influence transmission of disease. Similarly, contemporary engineering education includes explicit pedagogical strategies designed to help learners see the interdependence of components that make up an object under construction, such as a cell phone, a bridge or a space shuttle. Systems thinking in STEM — science, technology, engineering and mathematics — describes approaches embedded in the practice of engineering and biology that move beyond the fragmented knowledge of disciplinary content to a more holistic understanding of the field. In this way, practioners can see the forest while not losing sight of the trees. Systems thinking approaches emphasize the interdependence of components of dynamic systems and their interactions with other systems, including societal and environmental systems. Such approaches often involve analyzing emergent behaviour, which is how a system as a whole behaves in ways that go beyond what can be learned from studying the isolated components of that system.

Chemical reactions and processes, both in nature and industry, also function as parts of complex, dynamic and interdependent systems. Chemistry systems and sub-systems can be small and localized (much like a reaction in a laboratory flask), or large and diffuse (as is the distribution of carbon dioxide in the Earth's atmosphere, hydrosphere and biosphere). Moreover, chemistry systems and their components interact with many other systems, including the surrounding environment, leading to both beneficial and harmful effects on biological, ecological, physical, societal and other systems. Despite these interconnections, systems thinking is relatively unfamiliar to chemists and chemistry educators. The learning objectives for chemistry programs at both the high school and university level rarely include substantial and explicit emphasis on strategies that move beyond understanding isolated chemical reactions and processes to envelop systems thinking.

This lack of a systems thinking orientation has important implications for the education of practicing chemists and of those who intend to work in closely related molecular sciences, such as biochemistry and molecular biology, of which chemistry is an important pillar. If we do not pay due attention to systems thinking we will miss opportunities to motivate secondary and post-secondary students to connect their study of chemistry to important issues in their lives.

The reticence of chemistry educators to emphasize systems thinking can be rationalized in terms of concerns about overcrowded curricula; faculty inertia and the lack of a knowledge base outside of disciplinary specializations; the readiness, capacities, and expectations of students in particular settings; accreditation and standardized examination constraints; and the need to develop appropriate assessments. These challenges, which hinder the reorientation of chemistry education to take on systems thinking, are well worth addressing. To do this, we can make use of lessons learned in engineering, biology and other branches of science that have long embraced systems approaches in both education and practice.

Why systems thinking in chemistry?

Two important strands of argument support the case for reorienting chemistry education today.

First, the current systems of chemistry education, particularly at the undergraduate level, face challenges that can be addressed by approaches that incorporate systems thinking. Chemistry education researchers have documented the urgent need for the transformation of current approaches to teaching chemistry. The crucial first course in many university undergraduate chemistry programmes — which serves a small number of chemistry majors and a large number of students embarking on careers related to life sciences and engineering — has been described as "a disjointed trot through a host of unrelated topics" (*J. Chem. Educ.* **87**, 231–232; 2010). General chemistry students at the post-secondary level experience numerous isolated facts — theoretical concepts of apparently little relevance to everyday life or to problems faced in a slightly different discipline of chemistry to that in which the concepts were originally introduced. Additionally, there remains an overemphasis on preparing all undergraduate chemistry students for further study in chemistry rather than on providing them with the fundamental understanding of molecular-level phenomena that will serve their needs as future scientists, engineers and informed citizens (*Chemistry Education: Best Practices, Innovative Strategies and New Technologies.* Wiley, Weinheim, 3–26; 2015). Incorporation of systems thinking into chemistry education offers opportunities to extend the students' comprehension of chemistry far beyond what is achievable through rote learning. Such a change would enhance understanding of chemistry concepts and principles through their study in rich contexts. These include developing an appreciation of the place of chemistry in the wider world through analysing the linkages between chemical systems and physical, biological, ecological and human systems (the latter include legal and regulatory systems, social and behavioural systems, and economic and political systems).

Second, the sustainability challenges faced by today's planetary and societal systems require those in the chemical sciences, as well as collaborators from other disciplines, to adopt systems thinking approaches. Potential challenges include finding cleaner energy sources, developing cost-effective ways of purifying water, increasing soil quality and crop yields, exploring alternative forms of waste disposal, avoiding the exhaustion of crucial resources and protecting and preserving the planetary systems that sustain life. Oncoming challenges in health include the emergence and re-emergence of infectious diseases, the explosive growth of rates of non-communicable diseases and diseases of ageing, and the spread of antimicrobial resistance. Addressing any of these problems will require chemistry ingenuity to be combined with an appreciation of the interconnections of human, animal and environmental systems and of the role of effective, dynamic regulatory systems that can adapt quickly to changing circumstances. Achieving these objectives will be easier if those who study chemistry are educated in how to engage in systems thinking and cross-disciplinary approaches.

The case of neuroactive neonicotinoid pesticides provides one contemporary example of the need to fully consider interdependent systems for chemical substances. Widely used in agriculture because of the protection they provide against soil, timber, seed and animal pests, these pesticides have been implicated in the major decline of populations of honey bees, which are important vehicles in pollination. The growing evidence regarding the risks that neonicotinoids may pose to pollinators, ecosystems and systems of food production has prompted policy makers to propose or consider substantial restrictions on the use of neonicotinoids in agricultural systems around the world.

On considering the challenges and examples above, one can imagine a compelling set of potential benefits arising from reorienting chemistry education toward systems thinking:

- Strengthening opportunities for developing a more unified approach within the discipline of chemistry itself, which is too often taught, researched and practiced within compartmentalized subdisciplines.

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- Stronger engagement among the education, research and practice elements of chemistry, including the important interface between academia and industry.
- Enabling students to better understand the interactions between chemistry and other systems, including the physical, ecological and human systems of the planet, and develop the capacity for thinking and working across disciplinary boundaries, as a prerequisite for understanding the relevance of chemistry to comprehensively address twenty-first century challenges, including sustainable development.
- Enabling the development of an evidence-based approach to thinking about, understanding and responding to risk.
- Providing a framework for projecting chemistry as a ‘science for society’ that can help to create positive attitudes towards the discipline from the media, public and policy makers.

Strategies for introducing systems thinking

Very little literature explicitly describes systems thinking in chemistry education. Moreover, none of this literature addresses the comprehensive reorientation called for (*Nat. Chem.* **8**, 393–396; 2016) or outlined here. However, many approaches to tackling learning challenges involve strategies for introducing aspects of systems thinking to learners. Here, students' viewpoints can be widened if they look beyond the trees and think in terms of the forest. Engaging in ‘forest thinking’ enables students to consider changes over time, seeing data and concepts in rich contexts and by using case-based and problem-based approaches to learning (*ACS Sustainable Chem. Eng.* **2**, 2488–2494; 2014). At the pre-college level in the USA, the approach of the Next Generation Science Standards (*Next Generation Science Standards*. www.nextgenscience.org) and the National Academies' Framework on which they are based is to adopt three-dimensional learning. This combines core ideas, practices and cross-cutting concepts, placing particular emphasis on concepts that help students explore connections across different domains of science. Importantly, attention is specifically focused on understanding systems. Research into learning progressions (*Chem. Educ. Res. Pract.* **15**, 10–23; 2014) provides insights into how student chemistry thinking evolves and how the development can link with the efforts of their educators to teach theory, relevance, applications and consequences. Educational approaches that introduce green chemistry and engineering principles, and life cycle analysis provide entry points for considering overlaps between the boundaries of different systems. A variety of tools can assist in visualizing systems and the interactions between their components, including causal loop diagrams, concept mapping and dynamic systems modelling (*Learning Objectives and Strategies for Infusing Systems Thinking into (Post)-Secondary General Chemistry Education.* 100th Canadian Society for Chemistry Conference, Toronto, ON; May 30, 2017)

A framework for analysis

In the context of introducing systems thinking into chemistry education, it is pertinent to ask a number of questions. What are the chemistry systems that need to be understood? How do learners acquire an understanding of systems concepts and the ability to use systems tools and processes? What are the important interactions between the chemistry system and other systems? How can educators facilitate the acquisition, by learners, of the conceptual understanding and range of knowledge of the other systems that is necessary for a systems thinking approach to be meaningful?

The questions above may be addressed by making use of a proposed framework for analysis (FIG. 1) (*Learning Objectives and Strategies for Infusing Systems Thinking into (Post)-Secondary General Chemistry Education.* 100th Canadian Society for Chemistry Conference, Toronto, ON; May 30, 2017). The chemistry learner is placed at the centre of this framework, which comprises three nodes or central elements that contribute to the understanding of the interdependent components within and among the complex and dynamic systems involved in student learning. The learner systems node explores and describes the processes at work for learners, which include taxonomies of learning domains, learning theories, learning progressions, models for the phases of memory, the transition from rote to meaningful learning and social contexts for learning. The chemistry teaching and learning node focuses on features of learning processes applied to the unique challenges of learning chemistry. These include the use of pedagogical content knowledge; analysis of how the intended curriculum is enacted, assessed, learned and applied; and student learning outcomes that include

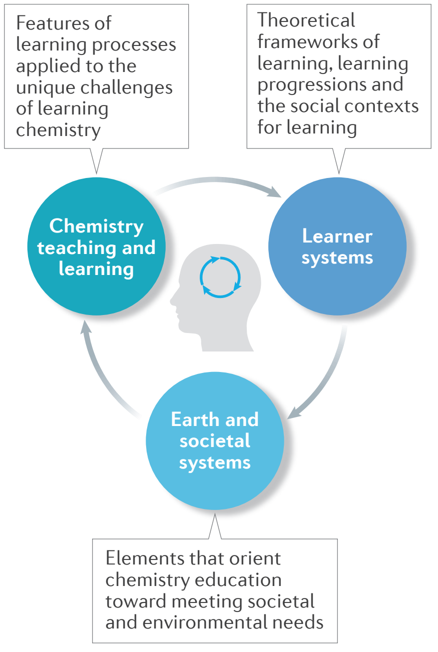

Figure 1 | **A framework for analysis of systems thinking in chemistry education.** The framework comprises three nodes or subsystems: learner systems, chemistry teaching and learning, and earth and societal systems.

responsibility for the safe and sustainable use of chemicals, chemical reactions and technologies. The earth and societal systems node orients chemistry education toward meeting societal and environmental needs articulated in initiatives such as the UN Sustainable Development Goals and descriptions of the earth's planetary boundaries. Educational systems to address the interface of chemistry with earth and societal systems include green chemistry and sustainability education, and use tools such as life cycle analysis.

Integrating systems thinking into practice

Required now is the development of new systems-oriented approaches to secondary school, high school and undergraduate chemistry courses, including gateway introductory post-high-school chemistry courses that serve both future chemists and many other future scientists. New learning resources designed to support such teaching are also needed

A project initiated in 2017 by the International Union of Pure & Applied Chemistry (IUPAC) and supported by the International Organization for Chemical Sciences in Development (IOCD), with the participation of 18 global leaders in chemistry education, has the goal of developing learning objectives and strategies for integrating systems thinking into general undergraduate chemistry education. It will use the framework (FIG. 1) of the three interconnected nodes of learner systems, chemistry learning and teaching, and earth and societal systems as a starting point.

Reorienting chemistry education through systems thinking can benefit students' learning of the subject. It can also enhance chemistry's impact as a science for the benefit of society, further strengthening its already considerable capacity to contribute to addressing global problems and advancing global sustainable development. These will be ample rewards for making an effort that will challenge traditional approaches to teaching this vitally important discipline.

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Competing interests
The authors declare no competing interests.