Next hundred years: systems thinking to educate about the molecular basis of sustainability

Abstract In the context of IUPAC's 2019 centenary celebration in Paris, we look back on how the world has changed over IUPAC's first one hundred years, and then look forward to the complex and rapid ways in which society and the environment are changing as we enter IUPAC's second century. In this article, we discuss why systems thinking will be increasingly important to chemistry and describe the IUPAC Systems Thinking in Chemistry Education (STICE) project, which sets out a framework to reorient chemistry education to more meaningfully equip students and the public to address emerging global challenges.
Keywords Chemistry education, systems thinking, sustainability, IUPAC Centenary.

Résumé **Pour les cent ans à venir : réflexions sur l'enseignement de la chimie et la durabilité**
Dans le cadre de la célébration du centenaire de l'IUPAC à Paris, nous avons regardé comment était le monde à la naissance de cette organisation, puis comment nous pourrions l'imaginer dans cent ans, vus la complexité et la rapidité de l'évolution de la société et l'environnement. L'enseignement de la chimie devra également évoluer, avec une part de plus en plus importante de la pensée systémique. Le projet « IUPAC Systems Thinking in Chemistry Education » (STICE) a pour but d'encadrer la réorientation de cet enseignement afin de mieux outiller les étudiants et le public pour qu'ils puissent faire face aux nouveaux défis mondiaux.
Mots-clés Enseignement de la chimie, pensée systémique, durabilité, IUPAC.

As the global chemistry community celebrates the 100th Anniversary of the establishment of the International Union of Pure and Applied Chemistry (IUPAC), we look back to what the world was like a hundred years ago and then forward to imagine how the world of chemistry and of chemistry education will need to change over the next hundred years.

What was the world like in 1919, when IUPAC was founded?

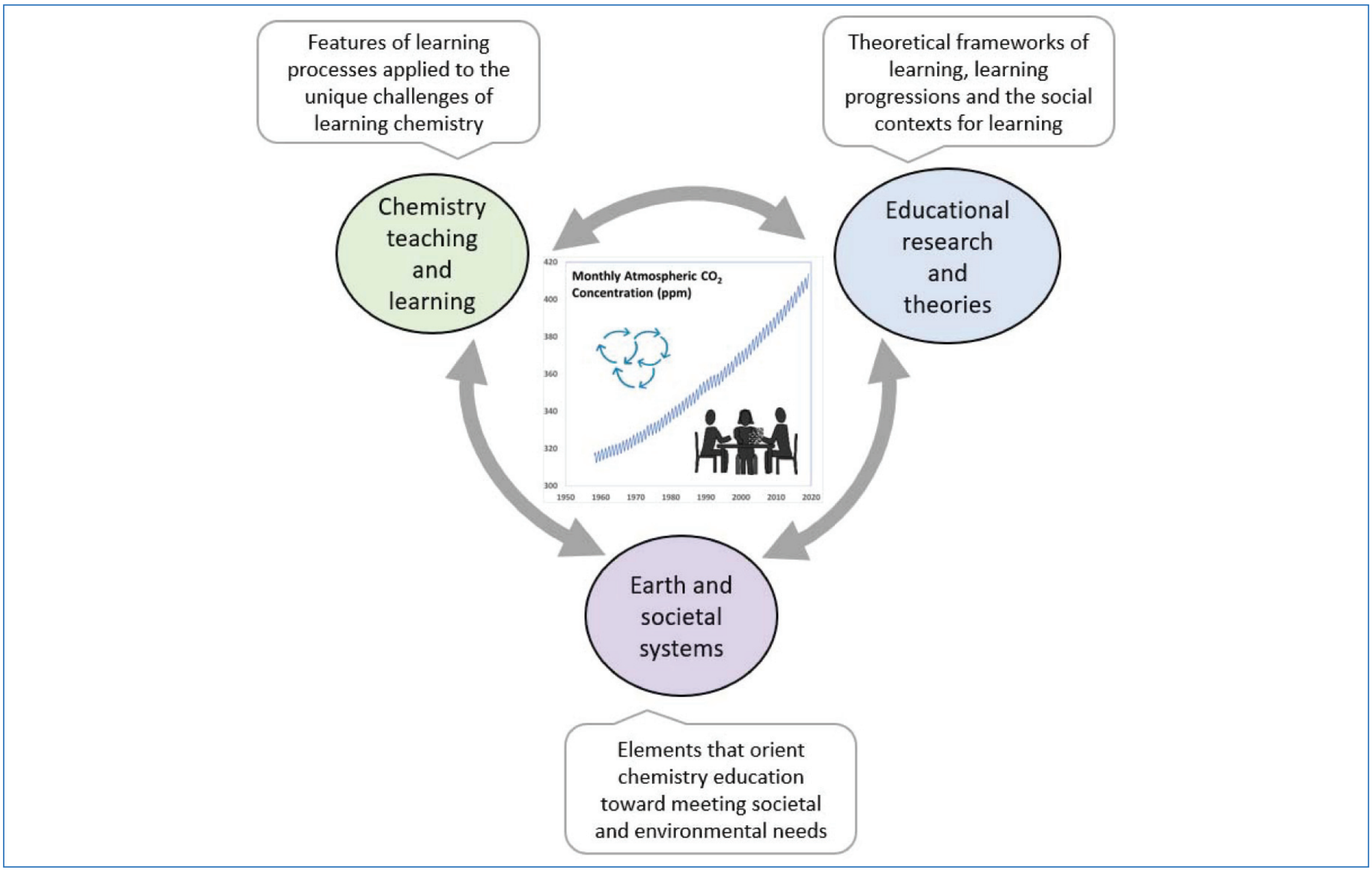
The first IUPAC members in 1919 saw transitions that year to remarkable new technologies and processes. This included the invention of both the rotary dial telephone, which converted sound into electrical impulses and the harnessing of electricity through the invention of the electric toaster that controlled the recently discovered Maillard reaction responsible for browning bread. And of particular importance to chemists in 1919, Fritz Haber received a controversial Nobel Prize in chemistry for "turning air into bread". The 1919 Nobel Prize recognized the importance of the Haber-Bosch reaction for converting nitrogen and hydrogen gas into ammonia – creating the fixed nitrogen needed to prevent large scale human starvation in the world. Part of the complexity of that Nobel Prize was Haber's key role in leading the insidious development to use chemical weapons on the battlefield – 1919 witnessed the signing of the Versailles/Paris Peace Treaty, which marked the end of World War I, also called "the Chemists' War."

Can we imagine the world of 2119?

Fast forward one hundred years from our 2019 Paris celebration of IUPAC's Centenary. What transitions will society and our planet have undergone? What role will chemistry have played in understanding challenges and contributing to solutions? Can we imagine what chemists in 2119, perhaps gathered again in Paris for a world chemistry congress, might say were important ways in which IUPAC worked out its mission over its second hundred years, namely to: "[…] *apply and communicate chemical knowledge for the benefit of humankind and the world*", and "*foster sustainable development, provide a common language for chemistry, and advocate the free exchange of scientific information*?" [1].

What is the role for chemistry over IUPAC's second hundred years?

It is increasingly evident in 2019 how urgent is the need for chemistry to play a much greater role in sustainable development, and to apply knowledge of chemistry for the benefit of humankind and the world. There is no denying either the rate at which our world has changed during the first hundred years of IUPAC or the severity of the global challenges faced in 2019 by humanity and the environment. Analysis of the "great acceleration" of human activity from the 1950s to present has led to recommendations by the professional association of geologists that the Holocene Epoch, a period of over 10,000 years of stable climate, has been replaced by the Anthropocene Epoch, defined by the human imprint on our planet [2]. Global headlines in the first few months of IUPAC's centenary year have highlighted the crisis of the loss of biodiversity, with over one million species facing extinction [3] and the recorded measurement of 415 ppm of atmospheric carbon dioxide at the Mauna Loa observatory, the highest atmospheric concentration since the evolution of humans [4]. The implications of the climate crisis are evident, with 467 traceable pathways for the impact on human health, water, food, economy, infrastructure and security by multiple climate hazards [5]. Sustainability science, as expressed in global initiatives such as the UN Sustainable Development Goals (UNSDG) [6] and the Planetary Boundaries framework [7] are tackling those challenges, but the "central science",



Systems Thinking in Chemistry Education framework, developed by the IUPAC STICE project.

profession of chemistry, is neither central nor especially visible at the centre of those sustainability initiatives. This, despite the fact that many of the indicators for trends marking the transition to the Anthropocene Epoch and metrics used by both the planetary boundaries and UNSDG frameworks are quantified by chemical parameters and measurements.

How will the profession of chemistry respond over the next century to the rapid and complex changes facing our planet? And what role will chemistry education need to play in that response?

What kind of chemistry education will be needed over the next hundred years?

"*Complexity requires specialization in the pursuit of discovery as we deepen our understanding of the modern world and create the knowledge needed to resolve current dilemmas and improve the quality of life.*

In this process, we continually ***fractionate knowledge****, analyzing the pieces in greater and greater depth. We have trained our 20^{th} century professional quite well in this task – it's a global strength we must sustain – but what additional skill will be demanded of 21^{st} century leaders?*

Joseph Bordogna, 1991 [8]

Analysis of two concurrent challenges suggests a substantial reorientation for chemistry education. First, chemistry education researchers have identified the urgent need to transform the way chemistry is taught and learned, especially in gateway secondary and post-secondary chemistry courses that serve crucial roles in the education of many different science and engineering professionals. Students often experience chemistry exclusively as "fractionated knowledge", presented as a myriad of isolated facts and concepts, strongly emphasizing mathematical calculations and with challenging symbolic representations [9]. This makes it difficult for students to apply what they learn to everyday life or global challenges, all of which require interdisciplinary insights and higher order skills. Second, the complexity of 21^{st} century sustainability challenges requires learners equipped to understand and address the interconnected scientific, technological, societal, and environmental systems in which the activities of chemistry to analyze, synthesize, and transform matter play such a crucial part.

Systems thinking in chemistry education

An IUPAC Systems Thinking in Chemistry Education (STICE) project, which is also supported by the International Organization for Chemical Sciences in Development (IOCD), was established in 2017 with the goal of reorienting chemistry education through systems thinking as one way to address the dual challenges of reforming chemistry education and helping equip learners to address the complex challenges society and the environment are experiencing [10]. Systems thinking has been defined as "the ability to understand and interpret complex systems" and involves: "visualizing the interconnections and relationships between the parts in the system; examining behaviors that change over time; and examining how systems-level phenomena emerge from interactions between the system's parts" [11]. A framework has been developed by the IUPAC STICE project group to visualize how systems thinking might be applied to chemistry education. As shown in the *figure*, learners are visualized at the centre of a system, with three interconnected nodes, or subsystems: the *Learner systems node*, which focuses on how we learn, including theoretical frameworks of learning, learning progressions, and the social contexts of learning; the *Chemistry teaching and learning node*, which focuses on the unique features of learning processes, as applied to the challenges of learning chemistry; and the *Earth and societal systems node*, which focuses on elements that orient chemistry toward meeting societal and environmental needs [12].

In the December 2019 special issue of the *Journal of Chemical Education*, authors have explored ways in which systems thinking approaches may: enhance students' knowledge, skills, and values in chemistry through a focus on the interconnections between different chemical phenomena; improve students' knowledge of the influence of chemistry on planetary and societal issues; and prepare students to make informed decisions and to address the complex global challenges of the 21st century [12-13].

The molecular basis of sustainability

The Earth and societal systems working group of the IUPAC STICE project has focused attention on a key question for next century: how can chemistry education more meaningfully integrate elements that address Earth and societal needs? The group suggests that the "molecular basis of sustainability," defined 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*" [14], should become a central guiding theme for chemistry education, particularly for gateway first year chemistry courses in tertiary education [15].

Can we look into the future and imagine a Paris 2119 celebration of IUPAC's second hundred years, where delegates review with satisfaction the many ways in which the profession of chemistry became widely recognized as making fundamental contributions to understanding the complex challenges of the previous century, while contributing meaningfully to finding solutions?

The authors thank all of the members of the IUPAC STICE project task force, and the many students and educators who are exploring, testing, and further developing the use of systems thinking approaches in the context of chemistry education. The project group is grateful to IUPAC and IOCD for financial support for IUPAC Project # 2017-010-1-050 (https://iupac.org/project/2017-010-1-050), and to the World Chemistry Congress organizing committee for featuring systems thinking in chemistry education in the scientific program.

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Peter MAHAFFY*,
Professor of Chemistry at the King's University, Edmonton, AB (Canada), and Director, the King's Centre for Visualization of Science.
Stephen MATLIN,
Adjunct Professor, Institute of Global Health Innovation, Imperial College London, and International Organization for Chemical Sciences in Development, Namur (Belgium).

*peter.mahaffy@kingsu.ca