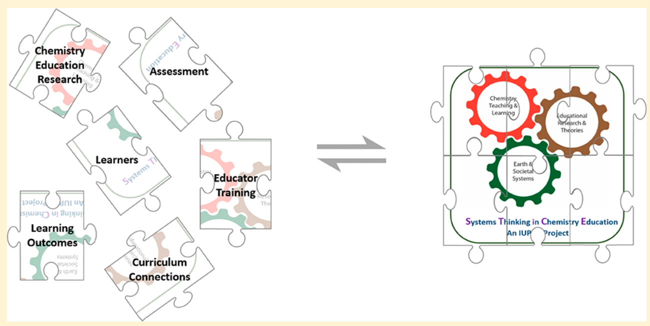
JOURNAL OF CHEMICAL EDUCATION
Article
Cite This: J. Chem. Educ. 2019, 96, 3000−3005
pubs.acs.org/jchemeduc

Future Directions for Systems Thinking in Chemistry Education: Putting the Pieces Together

Alison B. Flynn,[†] MaryKay Orgill,[‡] Felix M. Ho,[§] Sarah York,[‡] Stephen A. Matlin,[∥,⊥] David J. C. Constable,[#] and Peter G. Mahaffy*[,∇]

[†]Department of Chemistry and Biomolecular Sciences, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada
[‡]Department of Chemistry and Biochemistry, University of Nevada, Las Vegas, Las Vegas, Nevada 89154-4003, United States
[§]Department of Chemistry, Ångström Laboratory, Uppsala University, Uppsala 75120, Sweden
[∥]Institute of Global Health Innovation, Imperial College London, London SW7 2AZ, United Kingdom
[⊥]International Organization for Chemical Sciences in Development, Namur B-5000, Belgium
[#]ACS Green Chemistry Institute, 1155 16th Street, NW, Washington, D.C. 20036, United States
[∇]Department of Chemistry and the King's Centre for Visualization in Science, The King's University, Edmonton, Alberta T6B 2H3, Canada



ABSTRACT: The International Union of Pure & Applied Chemistry (IUPAC) launched a global project in 2017 to infuse systems thinking into chemistry education, motivated in part by the desire to help equip chemists and citizens to better address the complex, global challenges our society currently faces. One important early outcome of the IUPAC Systems Thinking in Chemistry Education (STICE) project is this special issue of the *Journal of Chemical Education*, which provides a key reference point for the rapidly emerging literature on the incorporation of systems thinking into chemistry education, including its application to green and sustainable chemistry. The STICE project outcomes to date include reviewing systems thinking approaches in other STEM fields, articulating a framework for STICE, identifying aspects of learning theories relevant to learning systems thinking skills in chemistry, using systems thinking approaches to integrate green and sustainability chemistry concepts into university-level chemistry classrooms, and identifying considerations for assessing systems thinking in chemistry education. The authors of this article, who, with others, have provided leadership to the STICE project, conclude this *Journal*'s special issue by briefly reviewing progress to date and identifying three main areas of future work for the application of systems thinking in chemistry education: (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. Our intention is to recommend potential opportunities, stimulate conversations, and motivate actions required to successfully equip learners with systems thinking skills in chemistry, such that these learners, citizens of our countries and our planet, are better positioned to interpret and address complex global challenges.

KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Upper-Division Undergraduate, General Public, High-School/Introductory Chemistry, Curriculum, Environmental Chemistry, Problem Solving/Decision Making, Learning Theories, Green Chemistry, Sustainability, Systems Thinking*

■ INTRODUCTION

Although chemistry and chemical phenomena underlie and are connected to every dimension of modern life,[1] chemistry education as a whole has been criticized as being fragmented and disconnected from broader contexts.[2,3] Those fragments and disconnections limit learners' abilities to connect molecular-level particles and phenomena with macroscopic phenomena and their symbolic representations, as well as their abilities to determine how chemical processes impact and are impacted by the economic, social, environmental, and political contexts in which they occur.[4] While recognizing the connections among various chemical phenomena is certainly essential for practicing chemists, as well as the influence that chemistry has on many planetary and societal issues, a

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

Received: July 12, 2019
Revised: September 14, 2019
Published: October 29, 2019

DOI: 10.1021/acs.jchemed.9b00637
J. Chem. Educ. 2019, 96, 3000−3005

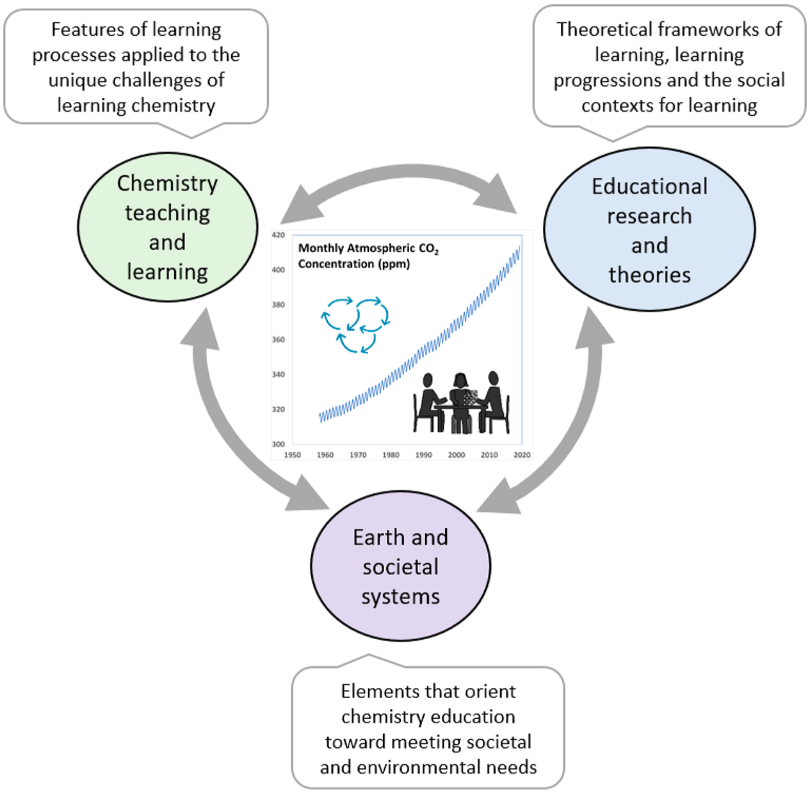


Figure 1. Framework for exploring the use of systems thinking in chemistry education.

compelling case is made that *all* people would benefit from the ability to interpret, explain, and make more informed decisions about issues with deep connections to chemistry,[5,6] such as those encountered when considering two global sustainability initiatives: the UN Sustainable Development Goals and the Planetary Boundaries framework. The Planetary Boundaries framework provides a quantitative assessment of nine Earth system processes of critical relevance for sustainable development,[7] and the UN Sustainable Development Goals provide "a blueprint for peace and prosperity for people and the planet", set out in the 2030 Agenda for Sustainable Development and adopted by all UN member states in 2015.[8,9] Many of the metrics for both of these global agendas are quantified by chemical parameters.[10]

The application of systems thinking approaches to chemistry education has been identified as an important strategy to facilitate moving from strictly reductionist to a more holistic view of chemistry education.[11] Systems thinking has been defined as "the ability to understand and interpret complex systems"[12] and involves[2] "(i) visualizing the interconnections and relationships between the parts in the system; (ii) examining behaviors that change over time; and (iii) examining how systems-level phenomena emerge from interactions between the system's parts". On the basis of their use in other educational contexts, systems thinking approaches show great promise to (a) enhance students' knowledge, skills, and values in chemistry through a focus on the interconnections between different chemical phenomena; (b) improve students' knowledge of the influence of chemistry on planetary and societal issues; and (c) prepare students to make informed decisions and to address the complex global challenges of the 21st century.

■ THE JOURNEY THUS FAR

While systems thinking approaches have been applied for some time to STEM education in engineering, earth and environmental sciences, and some areas of the life sciences,[13] the potentials of such approaches are just beginning to be explored for chemistry education. The International Union of Pure & Applied Chemistry (IUPAC) project *Systems Thinking in Chemistry Education* (STICE)[14] was created to catalyze and support efforts by the global chemistry education community to infuse systems thinking into chemistry education, with a particular focus on large enrollment introductory chemistry courses at the postsecondary and upper secondary levels. One substantial motivation was to facilitate embedding sustainability considerations into chemistry education.

Members of the STICE project team developed a framework to begin to conceptualize what systems thinking could mean in the context of chemistry education (Figure 1). The learner was visualized at the center of a system,[15] with three interconnected nodes, or subsystems: the *Educational Research and Theories 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. Three years into the STICE Project, this framework continues to provide a useful paradigm for future development and implementation of systems thinking approaches into chemistry education.

The STICE project recognizes that systems thinking approaches provide opportunities for chemistry educators to help students understand chemistry as a complex system of

DOI: 10.1021/acs.jchemed.9b00637
J. Chem. Educ. 2019, 96, 3000−3005

interconnected materials, processes, and products.[16] Systems thinking approaches make chemistry's connections to and potential influences on other disciplines more apparent and offer opportunities to more deeply embed green and sustainable chemistry principles and practices into mainstream chemistry courses.[10,17,18] However, engaging students in holistic thinking has not characterized typical approaches to chemistry education,[2,16,19] and many of the articles in this special issue have identified potential challenges in doing so. In the present article, we draw on this information to recommend potential areas for future work that will support the successful implementation of systems thinking approaches in chemistry education.

■ FUTURE DIRECTIONS: WHAT'S NEXT?

We have organized the potential areas for future work into three categories: (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. This list of suggestions and areas for future work is not comprehensive; rather, the list is intended to stimulate conversations and catalyze priority actions that will support the implementation of systems thinking in chemistry.

Developing Systems Thinking Resources for Chemistry Educators and Students

For systems thinking approaches to be effectively implemented in chemistry education and benefit learners, as a chemistry education community we need to identify the chemistry areas and interconnections that are appropriate for a systems thinking approach. We can identify those areas and interconnections based on an understanding of the learning needs of students in our chemistry courses and develop resources to support the educators who will implement the approach. In this section, we briefly discuss three priority activities needed to practically enact systems thinking approaches in chemistry education.

Priority: Develop and Explore Systems-Thinking-Related Learning Outcomes (LOs), Resources, Activities, and Assessments. Until now there has been little discussion or implementation of systems thinking in the context of chemistry education, so there is clearly a need to articulate LOs at course and program levels that guide teaching and learning, as well as inform the development of learning activities and assessments aligned with helping students to achieve such LOs. Although some chemistry-specific systems thinking LOs have been proposed,[4,17,20−22] future efforts should examine (1) if these LOs are truly appropriate for chemistry learners, (2) how these LOs can be assessed, and (3) how the attainment of these LOs contribute to a learner's understanding of chemistry and the place of chemistry in global phenomena and events. For example, in what ways will educators identify whether these proposed LOs or others do indeed capture essential learning outcomes for systems thinking that are needed by learners in later courses and posteducation settings?[23] The adaption and application of the LOs also remain to be explored for lifelong learning and continuing education contexts. Many opportunities remain to further explore and discuss the concrete details of what systems thinking entails in the context of chemistry education and which competencies students should demonstrate, informed by discussions from the perspective of other disciplines in the literature[24−27] and also evidenced by the breadth of contributions in this current special issue.

Educators who decide to implement a systems thinking approach will likely rely on prepared resources, at least initially. However, there are limited high-quality systems thinking teaching resources available.[12,19,28,29] Therefore, the successful employment of systems thinking approaches will require developing system thinking instructor guides, lesson plans, systems-thinking-oriented learning resources, and activities that can easily be adapted for course use. One example is an in-class learning activity related to the reactive nitrogen cycle.[30] Opportunities abound for educators to create innovative classroom activities to help students learn chemistry through a systems thinking lens and to learn systems thinking skills through a chemistry lens.[31]

Formative and summative assessment are critical to learning; however, there are currently limited methods for assessing, or measuring, systems thinking competencies (e.g., interviews, open-ended surveys, concept mapping, analysis of students' drawings). None of these methods appear to be validated and may not be easy to implement with large classes like general chemistry.[32−36] Chemistry-specific methods for evaluating students' applications of systems thinking skills could provide useful feedback to both instructor and students. A qualitative pilot study using an instrument for assessing student understanding using a systems thinking framework in chemistry education has been reported and offers insights into both the potential and challenges in creating coherent alignment.[37]

Priority: Connect Systems Thinking Approaches to Curriculum and Program Standards. Beyond individual learning activities and assessment at the course level, there is also a need to connect and integrate systems thinking at a higher level into curriculum design and education standards. We see great potential for integrating systems thinking approaches into chemistry education, both for improving conceptual understanding of chemical principles through highlighting issues such as emergence, levels of complexity, and dynamic interconnections, and at the same time for enhancing student understanding of fundamental aspects of systems behavior through chemical contexts.[13,38] However, systems thinking is clearly not the only approach for learning chemistry concepts and may not be the best approach for teaching and learning all chemistry concepts. Therefore, there is a need to identify the chemistry areas that are most appropriate for a systems thinking approach, as well as the areas that might be better addressed through other approaches. There is also a need to consider how a systems thinking approach might *expand* our understanding of what types of chemistry are important to include in the curriculum.[39] For example, one meaningful outcome of the STICE project is making more visible the value that systems thinking brings to existing efforts by the green and sustainable chemistry education community to infuse systems thinking in formal postsecondary education. Furthermore, institutional, national, and international educational standards play an influential, at times even regulatory, role in shaping the current and future directions of chemistry education. More investigations are needed into how systems thinking can meaningfully be formulated and integrated into such standards as well as how

DOI: 10.1021/acs.jchemed.9b00637
J. Chem. Educ. 2019, 96, 3000−3005

they can be fruitfully implemented, with due regard to local expectations, conditions, and regulatory frameworks.[40,41]

Priority: Design and Implement Chemistry Educator Training in Systems Thinking Approaches. Most chemistry educators at the secondary and tertiary levels have been enculturated into a reductionist approach to teaching and learning.[42−44] As a consequence, they will need professional development opportunities focused on building their understandings of the more holistic systems thinking perspective and demonstrating how to facilitate a systems thinking approach to learning chemistry.[35,42,44−47] Previous research with secondary teachers indicates that teachers learn how to facilitate student learning through a systems thinking approach most effectively when they both (i) participate directly in scaffolded, guided systems thinking activities[48,49] and (ii) receive didactic instruction about how to teach systems thinking concepts to their students.[50] Previous research also suggests that teachers need ongoing support *as* they attempt to enact these approaches in their classrooms.[47] It is reasonable to assume that tertiary chemistry educators will require similar types and levels of training and support. We urge the chemistry education community to consider ways and identify resources to develop, pilot, implement, and sustainably scale educator training opportunities. Such opportunities may include developing an open access virtual community through which exemplar systems thinking teaching materials can be vetted and shared, and where educators can request, receive, or provide support for each other.

Identifying Chemistry Education Research Needed To Investigate and Improve Systems Thinking Approaches

Intimately linked to the need for educational development efforts above is the need for rigorous, evidence-based chemistry education research (CER) on the effects and impact of such initiatives, with research areas that can include cognitive, affective, and long-term transfer of knowledge and skills, and equity, diversity, and inclusion in chemistry. Several researchers have undertaken CER in the related area of chemistry education for sustainability[51−53] which provides one good starting point for additional comparative work in systems thinking. *Cognitive studies* could include aspects associated with implementing systems thinking approaches in chemistry education, including, for example, identifying students' cognitive "prerequisites" for engaging in systems thinking, examining the *particularly important influence of systems thinking on learners' abilities to reason with complexity*, determining how learners' understandings of key concepts are influenced by systems thinking approaches to chemistry education, as well as potential issues such as student engagement and cognitive overload.[31] CER is also needed to determine the *affective* outcomes and implications of using systems thinking approaches in chemistry, as affect has been found to be correlated with both academic outcomes and learner engagement.[54−56] *Longitudinal studies* are needed on the impacts of a systems thinking approach on the students' long-term knowledge and their ability to *transfer* chemistry reasoning and skills to other academic and nonacademic contexts.[57] Finally, but certainly not least, the impacts of systems thinking approaches *for equity, diversity, and inclusion* need to be investigated. The ability to connect chemistry and the broader learning environment with experience, culture, and knowledge can have profound impacts on feelings of inclusion;[58] to that end, the explicit and multidisciplinary connections made through systems thinking approaches may engage students in conversations and experiences rarely encountered in chemistry classrooms.

Furthermore, there is clearly also a need for theoretical framework(s) that can inform and scaffold developing further material by practitioners and researchers alike. Frameworks from other disciplines such as the systems thinking hierarchy developed for geoscience education[2,26] can be good starting points, but further investigations and adaptions, grounded in research literature and evidence, will be necessary to adapt to the context of chemistry education.

Investigating Opportunities To Apply Chemistry-Related Systems Thinking Approaches to Broader Educational Contexts

While the greatest use of systems thinking approaches is found at primary, at secondary, and (less extensively) at undergraduate levels, chemistry-related systems thinking educational approaches also have the potential to have impact in graduate education and research, and far beyond formalized environments such as universities. Formalized school education accounts for a relatively brief, albeit intensive, part of the learning experience of individuals. For those who become chemistry professionals, continuing education programs aimed at developing proficiency using systems thinking approaches can be valuable tools for gaining new insights about chemistry and its role in society. Continuing education in systems thinking could also lead to finding new ways of collaborating with other disciplines for enhancing scientific, technological, and societal developments. Policy- and decision-makers in government, business, and industry would also benefit from outreach and professional development programs that provide them better understanding of chemistry's potential to contribute to future solutions and developments; such outreach and programs should take into account the complex decision-making environment with its wide range of (often competing) priorities, stakeholders from different parts of society, and considerations of the environment itself.

Learning beyond the years of formal education is necessary to continue supporting the development of members of society who can make informed and well-grounded decisions about their lives. In an ever more globalized world, the need for a systems thinking perspective is increasingly necessary for tackling complex and multifaceted issues and challenges such as environmental protection (including global issues like climate change), economic progress, and social equity, especially in cases where diverse, interconnected, and often competing interests and stakeholders are involved. Implementing systems thinking in a wide range of formal and informal chemistry education contexts has the potential to contribute to improved understanding of how chemistry, and science in general, substantially contributes to sustainable human development. This wide implementation can be compared with the call from Holbrook and Rannikmae[59] to shift the focus from "science through education" to "education through science". This wide implementation is also aligned with The Hague Ethical Guidelines[60] that include the following: "Formal and informal educational providers, enterprise, industry and civil society should cooperate to equip anybody working in chemistry and others with the necessary knowledge and tools to take responsibility for the benefit of humankind, the protection of the environment and to ensure relevant and meaningful engagement with the general public."

DOI: 10.1021/acs.jchemed.9b00637
J. Chem. Educ. 2019, 96, 3000−3005

CONCLUSIONS

Systems thinking approaches have the potential to help students learn chemistry and systems thinking in more powerful, connected, and meaningful ways. Ultimately, learners, citizens in our countries, would be better equipped to identify and leverage interconnections among various chemistry concepts, as well as the connections among chemistry and contemporary societal and environmental issues. Systems thinking in chemistry education is just starting to be explored, and while there are many opportunities and potential benefits, there are also challenges and risks, many of which relate to our knowledge gaps. To achieve the potential of systems thinking in chemistry education, we have identified the following key areas for future development: (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.

The authors and the STICE project team look forward to further efforts by the global chemistry education community to exploit the potential of systems thinking to help students and citizens to leverage a holistic understanding of chemistry to contribute more meaningfully and substantively to understanding and addressing important global challenges. We do not suggest a packaged and uniform approach to systems thinking in chemistry education. Rather, we place value in bringing together diverse perspectives to join, explore, test, and critique approaches to systems thinking, to better equip learners and ultimately to benefit our society.

AUTHOR INFORMATION

Corresponding Author

*E-mail: peter.mahaffy@kingsu.ca.

ORCID

Alison B. Flynn: 0000-0002-9240-1287
MaryKay Orgill: 0000-0002-8813-7698
Felix M. Ho: 0000-0001-7731-3396
Stephen A. Matlin: 0000-0002-8001-1425
Peter G. Mahaffy: 0000-0002-0650-7414

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank the members of the IUPAC STICE project and all of the authors who have contributed to this special issue of the *Journal of Chemical Education*, as well as the students and educators who are exploring, testing, and asking critical questions about 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, and F.M.H. acknowledges financial support from the Centre for Discipline-based Education Research (MINT) at Uppsala University.

REFERENCES

(1) Mahaffy, P. G. Chemistry Education and Human Activity. In *Chemistry Education: Best Practices, Innovative Strategies and New Technologies*; Garcia-Martinez, J., Serrano, E., Eds.; Wiley VCH: Weinheim, 2015; pp 3−26.

(2) Orgill, M.; York, S.; MacKellar, J. Introduction to systems thinking for the chemistry education community. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00169.

(3) Anastas, P. T. Beyond reductionist thinking in chemistry for sustainability. *Trends in Chem.* **2019**, *1*, 145−148.

(4) Mahaffy, P. The future shape of chemistry education. *Chem. Educ. Res. Pract.* **2004**, *5* (3), 229−245.

(5) Mahaffy, P. G.; Matlin, S. A.; Holme, T. A.; MacKellar, J. Systems thinking for educating about the molecular basis of sustainability. *Nat. Sustain.* **2019**, *2*, 362−370.

(6) National Academies of Sciences, Engineering, and Medicine. *Effective Chemistry Communication in Informal Environments*; The National Academies Press: Washington, DC, 2016. DOI: 10.17226/21790. https://www.nap.edu/catalog/21790/effective-chemistry-communication-in-informal-environments (accessed Sept 12, 2019).

(7) Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S. E.; Fetzer, I.; Bennett, E. M.; Biggs, R.; Carpenter, S. R.; de Vries, W.; de Wit, C. A.; Folke, C.; Gerten, D.; Heinke, J.; Mace, G. M.; Persson, L. M.; Ramanathen, V.; Reyers, B.; Sörlin, S. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, *347*, 736−747..

(8) United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development. Resolution Adopted by the General Assembly on 25 September 2015*; United Nations: New York, 2015; Document A/70/L.1. www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (accessed Sept 12, 2019).

(9) United Nations. *Sustainable Development Goals*; United Nations: New York, 2019. https://sustainabledevelopment.un.org/sdgs (accessed Sept 12, 2019).

(10) Mahaffy, P. G.; Matlin, S. A.; Whelan, J. M.; Holme, T. A. Integrating the Molecular Basis of Sustainability into General Chemistry through Systems Thinking. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00390.

(11) Mahaffy, P. G.; Brush, E. J.; Haack, J. A.; Ho, F. M. Journal of Chemical Education Call for Papers—Special Issue on Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry. *J. Chem. Educ.* **2018**, *95*, 1689−1691.

(12) Evagorou, M.; Korfiatis, K.; Nicolaou, C.; Constantinou, C. An investigation of the potential of interactive simulations for developing system thinking skills in elementary school: A Case study with fifth-graders. *Int. J. Sci. Educ.* **2009**, *31*, 655−674.

(13) York, S.; Lavi, R.; Dori, Y. J.; Orgill, M. Applications of systems thinking in STEM education. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00261.

(14) Learning Objectives and Strategies for Infusing Systems Thinking into (Post)-Secondary General Chemistry Education. IUPAC Project 2017-010-1-050. https://iupac.org/projects/project-details/?project_nr=2017-010-1-050 (accessed Sept 12, 2019).

(15) Mahaffy, P. G.; Krief, A.; Hopf, H.; Mehta, G.; Matlin, S. A. Reorienting chemistry education through systems thinking. *Nat. Rev. Chem.* **2018**, *2*, 0126.

(16) Constable, D. J. C.; Jiménez-González, C.; Matlin, S. A. Navigating Complexity Using Systems Thinking in Chemistry, with Implications for Chemistry Education. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00368.

(17) Holme, T. A. Incorporating Elements of Green and Sustainable Chemistry in General Chemistry via Systems Thinking. In *Integrating Green and Sustainable Chemistry Principles into Education*; Dicks, A. P., Bastin, L. D., Eds.; Elsevier: Amsterdam, 2019, pp 31−47.

(18) Hutchison, J. E. Systems thinking and green chemistry: Powerful levers for curricular change and adoption. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00334.

(19) Sabelli, N. H. Complexity, technology, science, and education. *J. Learn. Sci.* **2006**, *15*, 5−9.

(20) Hrin, T. N.; Milenković, D. D.; Segedinac, M.; Horvat, S. Systems thinking in chemistry classroom: The influence of systemic synthesis questions on its development and assessment. *Thinking Skills and Creativity* **2017**, *23*, 175−187.

DOI: 10.1021/acs.jchemed.9b00637
J. Chem. Educ. 2019, 96, 3000−3005

(21) Holme, T. A.; Hutchison, J. E. A central learning outcome for the central science. *J. Chem. Educ.* **2018**, *95*, 499−501.
(22) Mahaffy, P. G.; Krief, A. Systems Thinking to Reimagine Chemistry. ACS Webinar, 8 September 2016. https://www.acs.org/content/dam/acsorg/events/popular-chemsitry/Slides/2016-09-08-systems-thinking.pdf (accessed Sept 12, 2019).
(23) Stoyanovich, C.; Gandhi, A.; Flynn, A. B. Acid−Base Learning Outcomes for Students in an Introductory Organic Chemistry Course. *J. Chem. Educ.* **2015**, *92* (2), 220−229.
(24) Verhoeff, R. P.; Knippels, M.-C. P. J.; Gilissen, M. G. R.; Boersma, K. T. The theoretical nature of systems thinking. Perspectives on systems thinking in biology education. *Frontiers in Educ.* **2018**, *3*, 1−11.
(25) Arnold, R. D.; Wade, J. P. A definition of systems thinking: A systems approach. *Procedia Computer Science* **2015**, *44*, 669−678.
(26) Ben-Zvi-Assaraf, O.; Orion, N. Four case studies, six years later: Developing system thinking skills in junior high school and sustaining them over time. *J. Res. Sci. Teach.* **2010**, *47* (10), 1253−1280.
(27) Checkland, P. Systems Thinking. In *Rethinking Management Information Systems: An Interdisciplinary Perspective*; Currie, W., Galliers, B., Eds.; Oxford University Press: Oxford, 1992; pp 45−56.
(28) Forrester, J. W. System dynamics as an organizing framework for pre-college education. *Syst. Dynam. Rev.* **1993**, *9*, 183−194.
(29) Jacobson, M. J.; Wilensky, U. Complex systems in education: Scientific and educational importance and implications for the learning sciences. *J. Learn. Sci.* **2006**, *15*, 11−34.
(30) Holme, T. A. Systems Thinking as a Vehicle to Introduce Additional Computational Thinking Skills in General Chemistry. In *It's Just Math: Research on Students' Understanding of Chemistry and Mathematics*; Towns, M. H., Bain, K., Rodriguez, J.-M. G., Eds.; ACS Symposium Series; American Chemical Society: Washington, DC, 2019; Vol. *1316*, pp 239−250.
(31) Pazicni, S.; Flynn, A. Systems Thinking in Chemistry Education: Theoretical Challenges and Opportunities. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00416.
(32) Brandstadter, K.; Harms, U.; Großschedl, J. Assessing system thinking through different concept-mapping practices. *Int. J. Sci. Educ.* **2012**, *34*, 2147−2170.
(33) Gray, S. Measuring systems thinking. *Nat. Sustain.* **2018**, *1*, 388−389.
(34) Grohs, J. R.; Kirk, G. R.; Soledad, M. M.; Knight, D. B. Assessing systems thinking: a tool to measure complex reasoning through ill-structured problems. *Think. Skills. Creativ.* **2018**, *28*, 110−130, DOI: 10.1016/j.tsc.2018.03.003.
(35) Hmelo-Silver, C. E.; Azevedo, R. Understanding complex systems: Some core challenges. *J. Learn. Sci.* **2006**, *15*, 53−61.
(36) Wylie, J.; Sheehy, N.; McGuinness, C.; Orchard, G. Children's thinking about air pollution: A systems theory analysis. *Envir. Educ. Res.* **1998**, *4*, 117−137.
(37) Talanquer, V. Some insights into assessing chemical systems thinking. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00218.
(38) Ho, F. Turning challenges into opportunities for promoting systems thinking through chemistry education. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00309.
(39) Aubrecht, K. B.; Dori, Y. J.; Holme, T. A.; Levi, R.; Matlin, S. A.; Orgill, M.; Skaza-Acosta, H. Graphical tools for conceptualizing systems thinking in chemistry education. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00314.
(40) Chiu, M.-H.; Mamlok-Naaman, R.; Apotheker, J. Identifying Systems Thinking Components in the School Science Curricular Standards of Four Countries. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00298.
(41) Elmgren, M.; Ho, F.; Åkesson, E.; Schmid, S.; Towns, M. Comparison and evaluation of learning outcomes from an international perspective: Development of a best-practice process. *J. Chem. Educ.* **2015**, *92*, 427−432.
(42) Sweeney, L. B. Learning to connect the dots: Developing children's systems literacy. *Solutions Journal* **2012**, *3*, 55−62.
(43) Sweeney, L. B. All systems go! Developing a generation of "systems-smart" kids. In *EarthEd: Rethinking Education on a Changing Planet*; Assadourian, E., Ed.; World Watch Institute: Washington, DC, 2017; pp 141−153.
(44) Fisher, D. M. Reflections on teaching system dynamics modeling to secondary school students for over 20 years. *Systems* **2018**, *6*, 12.
(45) Lyneis, D. A. Bringing system dynamics to a school near you: Suggestions for introducing and sustaining system dynamics in K-12 education. Paper presented at the International System Dynamics Society Conference, Bergen, Norway, 2013. http://static.clexchange.org/ftp/newsletter/CLEx10.1.pdf (accessed Sept 12, 2019).
(46) Ossimitz, G. Teaching system dynamics and systems thinking in Austria and Germany. In *Proceedings of the 18th International Conference of the System Dynamics Society*; Davidson, P., Ford, D., Mashayekhi, A., Eds.; System Dynamics Society: Bergen, Norway, 2000. https://www.systemdynamics.org/assets/conferences/2000/PDFs/ossimitz.pdf (accessed Sept 12, 2019).
(47) Skaza, H.; Crippen, K. J.; Carroll, K. R. Teachers' barriers to introducing system dynamics in K-12 STEM curriculum. *Syst. Dynam. Rev.* **2013**, *29*, 157−169.
(48) Rosenkranzer, F.; Horsch, C.; Schuler, S.; Riess, W. Student teachers' pedagogical content knowledge for teaching systems thinking: Effects of different interventions. *Int. J. Sci. Educ.* **2017**, *39*, 1932−1951.
(49) Schuler, S.; Fanta, D.; Rosenkränzer, F.; Riess, W. Systems thinking within the scope of education for sustainable development (ESD) - A heuristic competence model as a basic for (science) teacher education. *J. Geogr. High. Educ.* **2018**, *42*, 192−204.
(50) Rosenkränzer, F.; Kramer, T.; Hörsch, C.; Schuler, S.; Riess, W. Promoting student teachers' content related knowledge in teaching systems thinking: Measuring effects of an intervention through evaluation a videotaped lesson. *Higher Educ. Studies* **2016**, *6*, 156−169.
(51) Burmeister, M.; Rauch, F.; Eilks, I. Education for sustainable development (ESD) and chemistry education. *Chem. Educ. Res. Pract.* **2012**, *13*, 59−68.
(52) Juntunen, M.; Aksela, M. Education for sustainable development in chemistry − Challenges, possibilities and pedagogical models in Finland and elsewhere. *Chem. Educ. Res. Pract.* **2014**, *15*, 488−500.
(53) Zoller, U. Science education for global sustainability: What is necessary for teaching, learning, and assessment strategies? *J. Chem. Educ.* **2012**, *89*, 297−300.
(54) Xu, X.; Lewis, J. E. Refinement of a Chemistry Attitude Measure for College Students. *J. Chem. Educ.* **2011**, *88* (5), 561−568.
(55) Villafañe, S. M.; Xu, X.; Raker, J. R. Self-Efficacy and Academic Performance in First-Semester Organic Chemistry: Testing a Model of Reciprocal Causation. *Chem. Educ. Res. Pract.* **2016**, *17* (4), 973−984.
(56) Liu, Y.; Ferrell, B.; Barbera, J.; Lewis, J. E. Development and Evaluation of a Chemistry-Specific Version of the Academic Motivation Scale (AMS-Chemistry). *Chem. Educ. Res. Pract.* **2017**, *18* (1), 191−213.
(57) *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*; Singer, S. R., Nielsen, N. R., Schweingruber, H. A., Eds.; National Academies Press: Washington, DC, 2015. http://www.nap.edu/download.php?record_id=13362 (accessed Sept 12, 2019).
(58) *Barriers and Opportunities for 2-Year and 4-Year STEM Degrees*; Malcom, S., Feder, M., Eds.; National Academies Press: Washington, DC, 2016. https://www.ncbi.nlm.nih.gov/books/NBK368176 (accessed Sept 12, 2019).
(59) Holbrook, J.; Rannikmae, M. The nature of science education for enhancing scientific literacy. *Int. J. Sci. Educ.* **2007**, *29*, 1347−1362.
(60) *The Hague Ethical Guidelines*; Organization for the Prohibition of Chemical Weapons: The Hague, 2015. https://www.opcw.org/hague-ethical-guidelines (accessed Sept 12, 2019).

DOI: 10.1021/acs.jchemed.9b00637
J. Chem. Educ. 2019, 96, 3000−3005