JOURNAL OF CHEMICAL EDUCATION

Article

Cite This: *J. Chem. Educ.* 2019, 96, 2777−2783

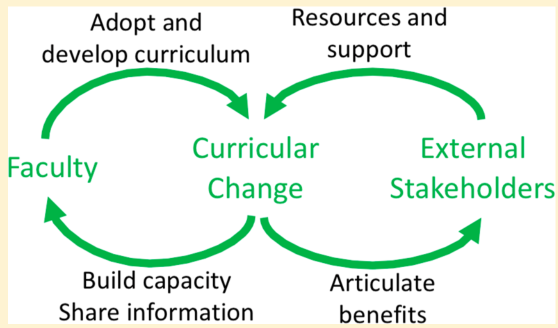
pubs.acs.org/jchemeduc

Systems Thinking and Green Chemistry: Powerful Levers for Curricular Change and Adoption

James E. Hutchison*

Department of Chemistry and Biochemistry and Materials Science Institute, 1253 University of Oregon, Eugene, Oregon 97403-1253, United States

ABSTRACT: Curricular change within the chemistry curriculum is often difficult and slow, in part because there are numerous specific barriers to implementation. However, a larger issue is that the curriculum, and the institutions that it is connected with, are complex systems. In the implementation of a new green chemistry curriculum for the organic teaching laboratory, we employed a systems-thinking approach to develop and disseminate the new curriculum. We identified five key leverage points where targeted efforts could yield significant gains in the design and implementation of the curriculum. Two key strategies that emerged from these efforts were the importance of expanding system boundaries to garner support for our efforts and building capacity of faculty to participate in curricular change. The systems approach contributed significantly to the successful introduction of green organic chemistry into the curriculum. Systems-based strategies are likely to catalyze future curricular-change efforts throughout the curriculum.



KEYWORDS: *Organic Chemistry, Green Chemistry, Curriculum, Laboratory Instruction, Inquiry-Based/Discovery Learning, Second-Year Undergraduate, Applications of Chemistry, Systems Thinking*

■ INTRODUCTION

In 1997, the University of Oregon (UO) Chemistry Department set out to revamp its traditional organic-chemistry laboratory curriculum by taking advantage of the new ideas that were emerging from green chemistry.[1] Green chemistry involves reducing the health and environmental impacts associated with the use and production of chemicals.[2] At the UO, we thought that green chemistry, specifically the use safer chemicals, would create a safer learning environment and reduce the need for expensive fume hoods in teaching laboratories.[3] As the project unfolded, it became clear that the development of greener lab experiments offered many other benefits. Experiments could be cheaper, generate less waste, be safer, modernize the curriculum, and appeal to student and faculty interests in environmental issues.[3] On the basis of early feedback on our efforts, it was clear that the educational materials that were being developed could be of interest to others in the community. At the same time, we were keenly aware that barriers to curricular change might limit adoption and the impact of the materials we were developing.

Thus, during the conception and development of these educational materials, we placed a strong emphasis on developing materials that would have the best chance of being adopted. There were some well-recognized barriers to avoid; for example, the exercises needed to be completed in a short period of time, typically about 3 h, and they had to work reliably; employ inexpensive reagents and solvents; and pose minimal risks to students, instructors, and staff.[3] In addition, they needed to teach specific laboratory skills and support the concepts and strategies covered in lecture courses.

However, as pointed out by Dancy and Henderson, the development of high-quality teaching materials that avoid the known barriers is insufficient to ensure adoption.[4] In discussing some of the barriers to adoption of active learning methods, they explain that the development and dissemination change model typically fails for a couple of key reasons. First, they argue that such models fail to engage those faculty who we hope will adopt new curriculum. They posit, and we agree, that engaging faculty in the change process is critical to robust curricular reform. Second, the model neglects the various situational factors (student preparation, departmental resources, instructor time, class size, etc.) that create barriers that often derail the adoption of curricular reforms. A recognition of engaging adopting faculty and developing educational materials that could be easily adapted to a variety of situations were at the heart of our strategy for developing the green chemistry curriculum at the UO.

Although we did not codify it as part of our approach at the time, a key to our successful strategy for development and dissemination was *systems thinking*.[5] Systems are collections of elements that work together to achieve a purpose. Our vision

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

Received: April 5, 2019
Revised: May 3, 2019
Published: May 23, 2019

DOI: 10.1021/acs.jchemed.9b00334
J. Chem. Educ. 2019, 96, 2777−2783

Figure 1. Concept map illustrating the interconnection and interdependency of the elements within the organic-chemistry-laboratory system. The lower portion of the map examines aspects of the traditional curriculum in place at the University of Oregon in 1997. The top portion of the map illustrates aspects related to a curriculum based upon green chemistry. The bubbles in the map correspond to system elements or concepts. The arrows indicate some of the important interconnections, whereas the labels characterize the nature of those interactions.

for the undergraduate laboratory was a system whose purpose was to teach the concepts, skills, and strategies within the context of reduced health and environmental impacts (i.e., green chemistry). The elements of the system were students, instructors, chemicals, facilities, and others. This system interacts with other systems, such as departments and their faculty and the broader institution. These elements and other systems are, in fact, the situational factors that Dancy and Henderson suggested are often neglected in curricular reform.[4] Like other systems, there are feedback loops and information flows within this system. By considering the organic teaching laboratory as a system in the curriculum-development and -dissemination process, it is possible to find key *leverage* points that improve the chances for adoption.

In this article, I describe how systems thinking and the idea of leverage points guided curriculum development and fueled adoption of green chemistry within the undergraduate organic-chemistry laboratory. The products of this effort, including more than 20 new laboratory exercises; a textbook, *Greener Organic Chemistry: Strategies, Tools and Laboratory Experiments*;[6] a searchable database, *Greener Educational Materials (GEMs) for Chemists*;[7] and a series of week-long workshops, *Green Chemistry in Education Workshops*, influenced hundreds of faculty and hundreds of thousands of students around the

DOI: 10.1021/acs.jchemed.9b00334
J. Chem. Educ. 2019, 96, 2777−2783

United States and the world.[7] Green chemistry has been adopted and infused into the curriculum at a wide variety of institutions around the world.[8] The consideration of systems thinking might prove helpful in the design, development and dissemination of other curricular reforms.

■ ORGANIC-CHEMISTRY TEACHING LAB AS A SYSTEM

A system is an interconnected set of elements that is organized to achieve a purpose. As mentioned above, the purpose of a laboratory course has traditionally been to teach laboratory skills. These courses often have other purposes such as complementing the lecture material. A revised purpose for a greener organic-chemistry laboratory is to accomplish these goals in the context of green chemistry. As we will see, establishing goals and defining purpose are powerful leverage points in a system. The interconnected elements of the system include students, instructors, staff, chemicals, lab facilities and equipment, the faculty, the department, the institution, external colleagues, graduate schools and employers, and donors or other external stakeholders, depending upon the boundaries that we place on the system. In some settings, these elements might be weakly connected, thus effectively creating a boundary around a smaller subset of the system. As I will describe below, strengthening the interconnections between these elements and expanding the boundaries can be beneficial in terms of creating conditions that are favorable for curricular change.

Once the elements of the system are identified, it is helpful to begin examining the nature of the interconnections. A concept map is a useful tool for this purpose.[9] Figure 1 is a concept map that examines the interconnectedness among the elements of the organic teaching laboratory with and without the incorporation of green chemistry. This map was constructed to examine the connections between elements and concepts that relate to the curriculum that existed in 1997 on the lower half and a greener curriculum on the top. Each bubble in the diagram represents a granular element of the system or describes a characteristic of an element. The arrows indicate *some* of the relationships between elements or concepts. One can envision many more connections and feedback arrows that would make the diagram more comprehensive but also less clear.

The concept map illustrates a number of opportunities to using systems thinking to find robust strategies for curricular change. The lower half illustrates the implications of using hazardous chemicals and suggests the opportunities created by decreasing or eliminating those hazards from the curriculum. Elimination of those hazards becomes a leverage point because it can reduce institutional liability, improve the learning environment, produce less hazardous waste, and decrease infrastructure (fume hood) needs. Decreased reliance on fume hoods, in turn, can reduce energy use and save the institution money, increase student−student and student−instructor interactions, and increase lab capacity (which in our case, reduced faculty workload, creating more time for curriculum development).

The upper half of the diagram illustrates some of the anticipated benefits of a greener curriculum (fewer hazardous chemicals, better student engagement, new chemistry and experiments, and a more positive public perception of chemistry) but also suggests some of the potential barriers to adoption that can be addressed through a systems-thinking approach.[3,7] For example, the introduction of new experiments requires examining the curriculum to find ways to incorporate new material into an already crowded curriculum. New experiments must be effective and thoroughly tested, or they will not be accepted by faculty. Adoption and further development of a greener curriculum will depend heavily on building faculty expertise and capacity. To achieve improved public perception of chemistry faculty, departments and universities will need to effectively communicate the impact and value of green chemistry.

Although not explicitly shown on the map, the diagram does suggest opportunities for feedback loops within the system. Cost savings can create opportunities for departments or institutions to reinvest in the curriculum. Better student engagement may create recruiting advantages, and improved student learning may advance relationships with employers and graduate schools. Opportunities may arise to enhance the public image of the department or institution, as well as increase philanthropic support for the curriculum, department, or institution. As I will describe below, important feedback loops can be engaged by expanding the boundary of the system and strengthening connections.

■ SYSTEMS-THINKING APPROACHES TO PROMOTE CURRICULAR CHANGE

Reflecting upon the success of our development and dissemination efforts for the greener organic-chemistry curriculum,[3,6−8,10] systems thinking played an essential role throughout this effort. From the inception of new educational materials and their relationship to the overall curriculum to our dissemination and capacity-building efforts, a systems approach contributed to the effectiveness and ultimate success at each step. In this section, I describe three key strategies that were inherent to our approach. The first was to tap leverage points, that is, those aspects of the system where a focused, strategic effort can have far reaching impacts in the system. Second, we expanded the boundaries of the system and strengthened interconnections with broader stakeholders to gain support for and enhance the impact of our efforts. Finally, we engaged faculty and built the capacity of the community to not only adopt and implement new educational materials but also actively participate in advancing the field at their institution and around the community.

Tapping Leverage Points

In her book, *Thinking in Systems*,[5] Meadows described 12 key leverage points that she described as places to intervene in a system where a small change can yield a substantial impact. She ranked these on the basis of their relative effectiveness. Five of the most effective leverage points that were critical to the success of our efforts and have potential for influencing future curricular changes are shown in Figure 2. The implementation of these within our program is summarized below.

Feedback Loops. Green chemistry offered a number of opportunities to take advantage of reinforcing feedback loops. Even with very tight systems boundaries (e.g., within the course itself), a reinforcing loop can result from better student engagement based upon the environmental relevance of the subject matter, enhancing the experience of the instructor and creating an environment where both the student and instructor can thrive. As one considers broadening the system boundaries, cost savings from the program that lead to

DOI: 10.1021/acs.jchemed.9b00334
J. Chem. Educ. 2019, 96, 2777−2783

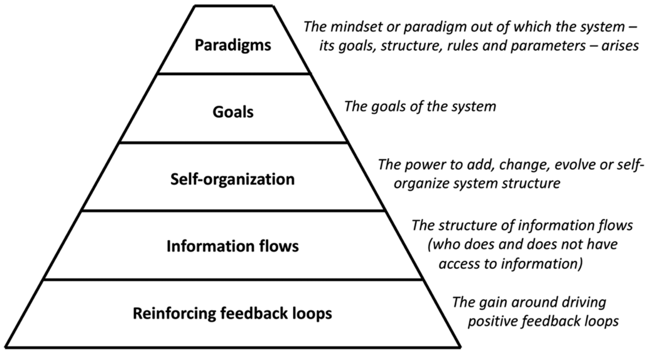


Figure 2. Selected leverage points for intervening in systems based upon the work of Meadows.[5] Although she described 12 leverage points, only those that were most influential in our curricular change are highlighted here. She ranked these 2, 3, 4, 6, and 7 out of 12. The leverage points near the top of the pyramid offer the greatest leverage. Meadows's descriptions of these leverage points are shown on the right.

reinvestment in the program or enhanced public perception might lead to philanthropic gifts from alumni or other stakeholders who generate virtuous circles that fuel further innovation. In our own efforts, taking advantage of student, donor, and public interest in more sustainable approaches helped us garner resources to build new facilities, secure the time for curriculum development, and navigate some of the politics of change.

Information Flows. In the context of curricular development and dissemination, information flow is a powerful leverage point. Providing access to educational materials is, of course, critical to encourage dissemination. Given the different system conditions (situations and perspectives) of potential adopters, we employed a range of dissemination strategies. By publishing a textbook,[6] we leveraged the established dissemination mechanisms of the publisher and delivered a comprehensive set of educational materials and supporting information. By publishing educational materials[3,9] in journals such as this one, information was provided in smaller, timely pieces that had been peer-reviewed. We also developed an online database (*Greener Educational Materials for Chemists*) that made a wide variety of materials freely available and searchable on the basis of the specific needs of the educator.[7] Finally, as described in more detail below, workshops and capacity-building activities[11] were employed as more contextualized mechanisms for information sharing, leading to faculty learning and successful adoption.[8]

In addition to sharing materials that can be used in a teaching laboratory or classroom (e.g., experimental protocols, worksheets, and instructor's manuals), an important aspect of information sharing involves communicating the basis for the development and use of the materials. Referring again to the work of Dancy and Henderson, real engagement of faculty in the process of curricular change is only successful if they understand the rationale behind the materials that they are trying to use or modify.[4] Thus, providing sufficient explanation for the basis of the concepts, techniques, and green-chemistry messages was central to our dissemination process at the UO. We found this enabled faculty to more readily adapt our innovations for use in their specific settings.

Self-Organization. The preceding discussion on faculty engagement leads nicely to the next leverage point: self-organization. Here, the leverage results from faculty having the ability and power to change the curriculum or curricular materials. This leverage point is exceedingly powerful because it changes an instructor's relationship to the curriculum. When an instructor is not only allowed but encouraged to make the curriculum their own, adoption is much more likely to occur. The fact that green chemistry is based upon principles, as opposed to prescription, is an important advantage because it makes it possible for faculty to tailor the curriculum to meet their needs while maintaining an emphasis on the principled learning outcomes. In our work, we aimed to leverage the principled approach and encouraged instructors to view the curriculum much like open-source software, something to build upon and tailor for their situation and interests. We encouraged this activity by supporting instructor efforts and celebrating these by asking them to report their successes during presentations at our annual *Green Chemistry in Education Workshops* (described below) and at national and regional scientific meetings.

Goals. One of the ways we were able to guide and support instructor innovation was to define clear goals for the curriculum and for the individual educational materials that were developed to support it. The goals established for the curriculum (to teach essential laboratory skills, modernize the curriculum, and support the lecture course, all in the context of greener chemistry principles and tools) were essential to help guide adopters but were also important to other stakeholders. For instance, there were concerns that a green chemistry curriculum might not be rigorous enough to prepare students for upper level course or undergraduate research. By establishing a goal around laboratory techniques *and* testing techniques through a practical final exam, one could demonstrate that the new curriculum and materials were not compromising student preparation. We made it a practice to state the goals for each laboratory exercise at the beginning of its description, addressing which chemical concepts, laboratory techniques and green-chemistry approaches were addressed. By clearly articulating these in our textbook and papers we established a practice for others to emulate and provided a framework for others to modify the educational materials without compromising the key goals of the activity.

Paradigms. The premise of green chemistry, that the design, production, and use of chemicals can be done in a way that meets societal needs while reducing impacts on health and the environment, is a paradigm shift. Paradigm shifts are one of the greatest sources of leverage and can result in wide-ranging and robust curricular change under the right conditions. As is the case in other systems, a paradigm shift also evokes strong resistance to preserve the status quo. In our efforts to develop and disseminate, we found that this leverage point was a double-edge sword. When conditions are not right, this shift in paradigm generated considerable resistance because it threatened the status quo. However, when conditions were right, the new paradigm helped guide curriculum development and created conditions to encourage adoption. For example, adoption of the new paradigm was effective when some type of change was already occurring (e.g., when there was significant turnover of staff in an institution or a significant change in curriculum precipitated by some other event). In those cases, adopters embraced the notion that the role of the chemist is to design for comprehensive product performance, focusing on environmental and economic performance as well as the traditional performance metrics. The new paradigm significantly changes the mindset of the chemist. Rather than focus

DOI: 10.1021/acs.jchemed.9b00334
J. Chem. Educ. 2019, 96, 2777−2783

on the yield of a particular reaction, one evaluates the overall process efficiency. Instead of focusing only on the hazards of reagents and solvents, one considers the hazards of the product, byproducts and waste generated. Evaluation of the product is not just its practical performance but also its end-of-life, the nature of the feedstock, its health or environmental impacts, and other impacts from its life cycle.

As mentioned above, resistance to maintain the status quo within the curriculum can be strong. However, even in the instances where the paradigm regarding the changing role of the chemist is not embraced, progress can be made by examining the educational materials and laboratory practices that are currently being used and asking why certain practices persist within the curriculum. Why are we using halogenated and aromatic solvents when there are safer alternatives? Why are we continuing to teach the Grignard reaction when there are much better ways to make carbon−carbon bonds? More generally, what is the desired learning outcome of the laboratory exercise? Is it necessary? Are there better practices? Are there ways to modernize the curriculum and make it greener at the same time?

Leverage points offer strategic opportunities to enhance the effectiveness of efforts to design and disseminate new curricula. By harnessing positive-feedback loops, ensuring free information flow, empowering faculty to modify and create, communicating clear goals regarding the purpose of the curriculum, and articulating an aspirational paradigm, one can increase the rates of adoption and establish a community that can contribute to the future success of the effort. In the next section, I will describe two strategies that we employed to garner support for the changes we sought to make and create conditions to increase the rate of adoption throughout the community.

■ STRATEGIES TO MAXIMIZE THE BENEFITS OF SYSTEMS THINKING

In the previous section, I described ways in which we harnessed key leverage points for curriculum development and dissemination. This section describes the specific strategies we used to tap into the benefits of the systems-thinking approach. These strategies helped us gain support for the curriculum-development and dissemination efforts and engaged faculty as partners in implementation of the emerging curriculum.

Expanding the Boundaries and Strengthening Connections

In the Introduction, I described the organic-chemistry lab as a system with a number of elements. The number and identity of those elements depends upon the boundaries defined for the system. As shown in Figure 3, the tightest possible boundary would likely be an individual instructor's teaching laboratory, where the instructor, students, lab facility, educational materials, lectures, and exams make up the system. As we begin to expand the boundaries, more people (other instructors and students, colleagues, and administrators), facilities, and external stakeholders are involved. Although expanded boundaries can lead to greater complexity, they almost always bring with them more resources and potential supporters. There are more opportunities to establish reinforcing feedback loops and to increase information flows. Note that Figure 3 ignores, for clarity, the fact that the department, institution, and outside world are also systems with system boundaries overlapping those shown in the figure.

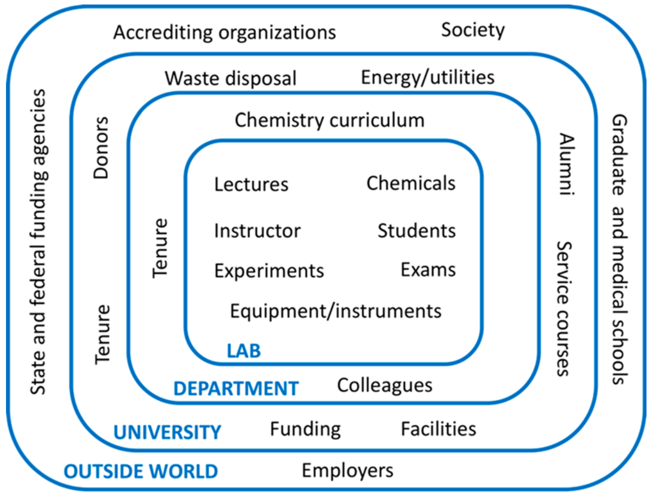


Figure 3. Four different system boundaries associated with a teaching-lab environment. The narrowest boundary that defines a system is that of the laboratory course. The elements of that system are shown within the inner boundary. As the boundaries are broadened to encompass the chemistry department, school and the outside world, an increasing number of elements are included, providing opportunities for greater feedback or leverage within the larger system.

In addition to expanding the boundaries of the system, one must build or strengthen the interconnections between the elements and consider the leverage points described above. In our own work, by illustrating the value of the curricular change to the departmental and university, we were able to gain support for curriculum development and laboratory renovations. Through the process of demonstrating the effectiveness of the curriculum and the importance of faculty capacity building to colleagues at the Green Chemistry Institute, the Environmental Protection Agency, and the National Science Foundation, we were able to secure funding to further catalyze the development, and active dissemination of the curriculum. In seeking to define system boundaries and strengthen connections, it is important to examine whether (and how) the new system elements, once connected, can contribute to the system's purpose. Those elements that have little impact or are weakly connected may provide little leverage.

Expanding the boundaries of the system to include more stakeholders (or other system elements) and strengthening interconnections between the elements creates new opportunities for leverage. For example, it is possible to create reinforcing feedback loops that support your efforts by identifying and strengthening ties to supportive stakeholders who also benefit from your success. Sharing information with strategic partners can serve to amplify messages, create broader support (and perhaps demand for curricular reform) throughout the broader system. Communication of goals and description of a new paradigm help establish shared interests between stakeholders within the system that can generate greater support for one's dissemination efforts or provide support and credibility (for example from academic adopters, graduate schools, and employers) that create conditions within the system that strengthen ties or create new feedback loops.

DOI: 10.1021/acs.jchemed.9b00334
J. Chem. Educ. 2019, 96, 2777−2783

Building Faculty Capacity To Leverage Systems Thinking

Shortly after our initial trial run of the greener organic-chemistry laboratory curriculum, we recognized that the develop and disseminate model[4] was insufficient to advance adoption of the new curriculum. Faculty faced a number of barriers to adopting the new curriculum, including insufficient knowledge about green chemistry, a lack of time to evaluate and select new experiments, and institutional resistance to change. To help faculty overcome these barriers, we ran a week-long *Green Chemistry in Education Workshop* each summer from 2001 to 2017.[7,8] The primary aim of the workshop was to support successful adoption of the curriculum at the participants' home institutions. Systems thinking was a key to the design of the workshop and was integrated as a topic in the workshop curriculum.

In developing the workshop, we recognized that each participant experienced unique system conditions within their institution; these are the *situational factors* referred to by Dancy and Henderson.[4] Each experienced different levels of institutional support, had different facilities, taught students with different levels of preparation, and had different levels of experience with green chemistry. This meant that they needed to develop tailored approaches to curricular change that was informed by their specific system conditions. In addition, many participants experienced negative feedback loops that inhibited adoption, such as limited time to evaluate or develop new educational materials. Finally, many of the participants were relatively isolated, meaning that their system boundaries were narrow.

A key to the success of the workshops was to showcase how other participants had successfully leveraged the resources and conditions within their institutions. Participants were selected from a broad range of institutions, including community colleges, primarily undergraduate four-year institutions, and research-intensive universities. Although the details of the strategy for employing systems thinking varied among the types of institutions, there were many aspects that united the groups, and participants could learn from those similar and different from them throughout the week. We brought back previous participants to present their *Success Stories* and serve as instructors, resources, and role models within the workshop. Each cohort of Success Story speakers represented the broad range of institutional types described above.

To help participants create greater leverage for adopting the curriculum, we worked with them to identify stakeholders within their system that could be most helpful to them and helped them think about how to strengthen connections with those stakeholders. We helped them establish nationwide networks through a focus on networking during the workshop. To this end, we began each workshop with a day-long networking event and provided opportunities to strengthen connections among participants throughout the week. We showed participants how expanding their system boundaries and strengthening connections with a broader group of stakeholders in and around their own institutions could garner the support or resources that they needed for success. The Success Story speakers, through their presentations and informal discussions with the participants, were able to illustrate how these approaches were successful in their own situations.

To address the barriers (and negative feedback) common during curricular change, we provided large blocks of laboratory time during the workshops for participants to rapidly evaluate dozens of possible experiments and get help troubleshooting any issues they had implementing them. This approach circumvented a significant barrier to adoption of a new laboratory experiment. The participant does not need to procure materials and equipment, carry out the experiment alone, and take the time troubleshoot the exercise if things do not work. Providing all the supplies and equipment, along with expertise, reduces barriers to adoption and gives participants confidence that the activity will work for them. The participants also learned to troubleshoot any problems with the experiments with the support of experienced staff, faculty, and graduate students who were present in the laboratories.

■ SUMMARY

On the basis of our experience using aspects of systems thinking in the development and dissemination of a greener organic-chemistry-laboratory curriculum we found important advantages in considering the curriculum as part of a broader system. By expanding the boundaries of the system and strengthening ties for key stakeholders, we were able to garner support for our efforts. We found key leverage points that were used to design the curriculum so that it could be more successfully adopted (and adapted) by others. By engaging faculty to modify and adapt, as well as building their capacity to leverage systems thinking, we were able to create and support a community that has taken responsibility for furthering the development and dissemination of the curriculum.

Future curricular change efforts may benefit from taking a systems-thinking approach to the design and dissemination of curricular materials. Although excellent educational materials are important and efforts to train faculty to adopt those materials are laudable, our experience suggests that a broader perspective is needed to create conditions that favor curricular change. Efforts that engage the system (faculty, students, curricula, departments, universities, and beyond) in a concerted manner, although difficult, are needed to catalyze curricular change.

■ AUTHOR INFORMATION

Corresponding Author

*hutch@uoregon.edu.

ORCID

James E. Hutchison: 0000-0003-2605-3226

Notes

The author declares no competing financial interest.

■ ACKNOWLEDGMENTS

I would like to thank Ken Doxsee and Julie Haack for their many contributions to the development and dissemination of the green organic chemistry laboratory curriculum at the University of Oregon, the National Science Foundation for their generous support of our development and dissemination efforts, and the many students and educators around the country who provided valuable feedback on the curriculum over the last 20 years.

■ REFERENCES

(1) *Green chemistry: Designing Chemistry for the Environment*; Anastas, P. T., Williamson, T. C., Eds.; ACS Symposium Series *626*; American Chemical Society: Washington, DC, 1996.

DOI: 10.1021/acs.jchemed.9b00334
J. Chem. Educ. 2019, 96, 2777−2783

(2) Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*; Oxford University Press Inc.: New York, 1998.
(3) Reed, S. M.; Hutchison, J. E. Green Chemistry in the Organic Teaching Laboratory: An Environmentally Benign Synthesis of Adipic Acid. *J. Chem. Educ.* **2000**, *77*, 1627−1629.
(4) Dancy, M.; Henderson, C. *Barriers and Promises in STEM Reform*; National Academies of Science: Washington, DC, 2008.
(5) Meadows, D. H. *Thinking in Systems: A Primer*; Earthscan: London, 2009.
(6) Doxsee, K.; Hutchison, J. E. *Green Organic Chemistry: Strategies, Tools, and Laboratory Experiments*; Cengage Learning: Boston, 2003.
(7) Haack, J. A.; Hutchison, J. E. Green Chemistry Education: 25 Years of Progress and 25 Years Ahead. *ACS Sustainable Chem. Eng.* **2016**, *4*, 5889−5896.
(8) *Green Chemistry Education: Changing the Course of Chemistry*; Anastas, P. T.; Levy, I. J.; Parent, K. E., Eds.; ACS Symposium Series *1011*; American Chemical Society: Washington, DC, 2009.
(9) Aubrecht, K. B.; Dori, Y. J.; Holme, T. A.; Levi, R.; Matlin, S. A.; Orgill, M.; Skaza-Acost, H. Graphical Tools for Conceptualizing Systems Thinking in Chemistry Education. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00314.
(10) (a) Warner, M. G.; Succaw, G. L.; Hutchison, J. E. Solventless Syntheses of Meso-tetraphenylporphyrin: New Experiments for a Greener Organic Chemistry Laboratory Curriculum. *Green Chem.* **2001**, *3*, 267−270. (b) McKenzie, L. C.; Huffman, L. M.; Parent, K. E.; Thompson, J.; Hutchison, J. E. Patterning Self-assembled Monolayers on Gold: Green Materials Chemistry in the Teaching Laboratory. *J. Chem. Educ.* **2004**, *81*, 545−548. (c) McKenzie, L. C.; Thompson, J. E.; Sullivan, R.; Hutchison, J. E. Green Chemical Processing in the Teaching Laboratory: A Convenient Liquid CO_2 Extraction of Natural Products. *Green Chem.* **2004**, *6*, 355−358. (d) McKenzie, L. C.; Huffman, L. M.; Hutchison, J. E. The Evolution of a Green Chemistry Laboratory Experiment: Greener Brominations of Stilbene. *J. Chem. Educ.* **2005**, *82*, 306−310.
(11) Kerr, M. E.; Brown, D. M.. Using Green Chemistry to Enhance Faculty Professional Development Opportunities. In *Green Chemistry Education: Changing the Course of Chemistry*, Anastas, P. T., Levy, I. J., Parent, K. E., Eds.; ACS Symposium Series *1011*, American Chemical Society: Washington, DC, 2009.

DOI: 10.1021/acs.jchemed.9b00334
J. Chem. Educ. 2019, 96, 2777−2783