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Experiential Learning To Promote Systems Thinking in Chemistry: Evaluating and Designing Sustainable Products in a Polymer Immersion Lab

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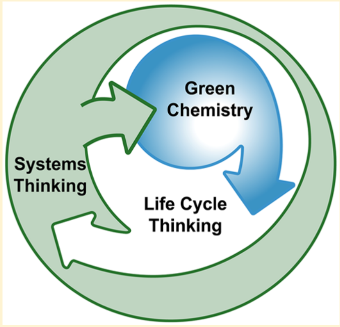
Supporting Information

ABSTRACT: The integrated application of green chemistry, life cycle thinking, and systems thinking has the potential to reduce environmental impacts related to the use and production of chemical products or materials. Life cycle and systems thinking are key perspectives needed to avoid the unintended consequences or unsubstantiated claims that inhibit development and adoption of more sustainable products. However, systems thinking is rarely taught in the chemistry curriculum. Students need experience evaluating the effects of products on societal and earth systems (i.e., using systems thinking) in order to anticipate trade-offs and make informed design decisions. To give students an immersive learning experience, we developed a sustainable product design project that brings together tools from green chemistry, life cycle thinking, and systems thinking. We found that this experiential learning approach gave students generalizable strategies for innovating and implementing sustainable practices in their current industrial positions. The project was divided into three workshops: in Workshop I they evaluated the life cycle impacts and toxicity for a material of concern, in Workshop II they measured the performance of this material and compared it to alternatives, and in Workshop III they designed a mock-product that was both high performing and environmentally friendly. We piloted this framework with master's students evaluating polymer foams for use in an infant car seat; however, we envision this project being suitable for a range of other types of products. Moreover, we have suggested ways to adapt the duration and sophistication of the workshops to make them appropriate for a variety of course levels.



KEYWORDS: *Systems Thinking, Green Chemistry, Upper-Division Undergraduate, Graduate Education/Research, Collaborative/Cooperative Learning, Hands-On Learning/Manipulatives, Polymer Chemistry, Applications of Chemistry*

■ INTRODUCTION

Green chemistry has gained considerable acceptance in both industry and academia.[1−4] As the world has grown more environmentally conscious, greener products and processes have become the focus of innovation and product development in industry.[5] In academia, green chemistry has improved laboratory safety and taught students strategies and techniques to reduce the environmental impacts of chemicals and chemical transformations.[4] Regardless of the setting, green chemistry solutions are intended to reduce environmental impacts while simultaneously maintaining or even improving performance. However, in many cases, changes made to green a product or process introduce unintended problems.[6] For example, products have been modified to use renewable carbon sources, and claims have been made that this change in feedstock inherently reduces environmental impacts. Although there are certain circumstances in which impacts are reduced, there are often net increases in environmental impacts when upstream effects (e.g., water and energy input) or functional sacrifices (e.g., decreased product performance) are not taken into consideration or fully evaluated.[7] Unintended consequences are not only detrimental because they can increase environmental impacts, but also because unsubstantiated sustainability claims can lead to consumer distrust of green technologies.

A more holistic approach to designing and evaluating products and processes is necessary to achieve the aims of green chemistry. Although green chemistry principles can be implemented to reduce environmental impacts, two additional approaches, life cycle thinking and systems thinking, are important for guiding decision making for more sustainable solutions. Life cycle thinking considers material impacts for a specific technological solution at each stage of the life cycle, from cradle to grave (or ideally from cradle to cradle). This accounting of impacts at each stage of life can be performed

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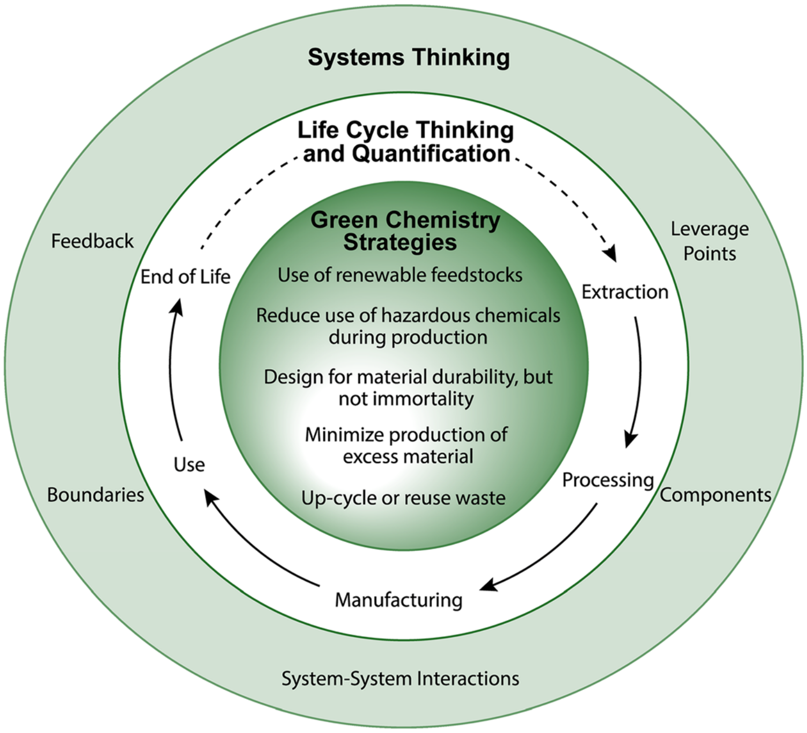

Figure 1. Complementary lenses to practical sustainable product design. Green chemistry is rooted in the 12 principles to reduce impacts. These principles can inspire change but require broader perspectives (life cycle and systems thinking) to assess trade-offs and practicality.

qualitatively, where it is referred to as life cycle thinking, or quantitatively, where it is referred to as a life cycle assessment. Systems thinking further expands the scope to consider how that specific technological solution impacts and is influenced by society, ecology, and other technologies. The complementary relationship among green chemistry, life cycle thinking, and systems thinking is illustrated in Figure 1.

In the figure, green chemistry is nested within life cycle thinking, and both of these are nested within systems thinking. In this context, the choice of green chemistry strategies can be informed by examining the relative impacts of competing solutions across the life cycle. By broadening the perspective out to the systems level, one can anticipate problems, challenges, and opportunities as a technological solution interfaces with the commercial sector, the environment, and society. We can use a children's car seat as an example product for thinking through these different lenses: green principles could drive exploration of the chemical hazards of the padding foam; life cycle thinking could expand on this to ask whether other types of foams have reduced end-of-life impacts; and systems thinking could further expand the scope to consider if an alternative foam with better end-of-life impacts has performance advantages, such as a reduced risk of accidental cracking during routine wear and tear. Using this combination of lenses can help students design and implement chemistry-based solutions that increase product performance while anticipating trade-offs and limiting unintended consequences.

The consideration of systems thinking in the chemistry curriculum has only recently received attention. Matlan et al. highlighted the need for modern chemistry education to use a systems approach in teaching, suggesting that students should work more broadly across disciplines and consider the relationships between chemistry and the rest of the world. The authors emphasized that chemistry is interconnected with a global future that is ethical and sustainable and that we need to stop treating it as a discipline that is isolated from human influence.[8] This call for a more integrated approach to chemistry pedagogy emphasized what we have also found to be true, students are seldom asked to think about how chemistry interacts with the world beyond the benchtop. Instead, chemistry is often reduced to the use or transformation of chemicals with little or no consideration of resource depletion, waste generation, or impacts on stakeholders and the ecosystem. Outside of chemistry education, systems thinking has received attention in earth and life science education.[9−11] However, the goal there has typically been to increase students' ability to identify or understand complex ecological webs or earth cycles, not to use the knowledge of this interconnectedness to develop technical solutions. Because chemistry as a discipline is uniquely positioned to offer technical solutions to real-world challenges (i.e., chemists introduce new chemicals and materials into the world), teaching chemistry students to think about innovation with a systems lens can be particularly advantageous.

Although many excellent resources have been previously developed to help educators incorporate green chemistry into the undergraduate teaching curriculum,[1,12−15] few tools are available to help educators incorporate systems thinking or even life cycle thinking. Academic courses and laboratories in chemistry typically focus on reductionist problem solving skills as opposed to examining the bigger picture. Recently, there has been some effort not only to familiarize students with green chemistry but to help students develop the tools to implement green principles on their own. In this light, Bode et al. developed lessons and discussion prompts aimed at teaching students to understand and generalize technically challenging life cycle assessments.[16] A couple of universities have begun offering sustainable product design courses to train business

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students to evaluate scientific facts and assertions.[17,18] These types of practical approaches to teaching green chemistry are important for making chemistry concepts approachable to students with a variety of career interests and expertise. Inspired by the call for students to practice using chemistry for a broad multidisciplinary purpose, we aimed at developing an immersive project that requires students to apply systems thinking to address a real-world problem. Herein, we describe a framework where students use systems thinking, along with life cycle thinking and green chemistry, to tackle a problem of industrial relevance.

■ SYSTEMS THINKING TO GUIDE GREEN CHEMISTRY

The basis for our approach is the realization that green chemistry principles can inspire innovation, but these principles alone do not give a perspective on the overall impacts of the changes made to a product or process. The multiple lenses needed for practical green product design (Figure 1) foster a holistic perspective that considers the impacts of an action on both the environment (through life cycle thinking) and societal and earth systems (through systems thinking). Life cycle thinking ensures that a green improvement at one stage of life does not have unrealized impacts elsewhere, and systems thinking considers the interconnections between *components* and anticipates ways in which action will be most beneficial for eliciting the desired system response.

This paper is not meant to give a comprehensive explanation of systems thinking concepts but rather to showcase how to leverage the strengths of systems thinking (along with life cycle thinking) to guide greener product or process design. The terms that relate to Figure 1 are italicized and discussed below, but for a detailed guide to systems thinking, we recommend *Thinking in Systems* by Donella Meadows.[19] A system is made up of a collection of *components* (people, things, infrastructure, etc.) that work together to influence the goal of the system. The scope of the components and therefore of the system is determined by the defined *boundaries*. No matter what the boundaries are, a system's components are interconnected and influential. These casual connections between components are termed *feedback loops*. Feedback loops can be complex and have delays between system intervention and observed effect. Systems are also affected by *system−system interactions*: feedback from other systems that influences the system of interest. Finally, systems have *leverage points*, wherein a small intervention can cause a major shift in system behavior.

In the context of greener consumer products, which provides the setting for the work described in this paper, some of the key components are students, chemicals, product designers, corporate investment, and regulatory laws. Possible use scenarios for the product influence the boundaries of the system. For example, the material may just be of interest within a teaching lab, it could be studied for companywide R&D, or the entire industry sector in which that material is used could be the focus. The influence of other systems can have a significant impact; for example, changes in FDA regulations will influence a sunscreen company's R&D, and activist bloggers often motivate innovation at consumer-facing companies.

Figure 2 focuses on the interconnection of the three complementary lenses from Figure 1. The benefits of using these approaches together are achieved through an iterative process, as depicted in Figure 2. This process is the equivalent of zooming in and out among the lenses in Figure 1; for example, working outward from green chemistry to life cycle and systems thinking, then back inward to green chemistry solutions. There is no right level to start at, but consideration of all of the perspectives is key to designing an innovative and practical solution that can prevent unintended consequences. For example, the motivation for innovation can come from safety concerns over a specific chemical (e.g., a green chemistry starting point), or the motivation can come from a desire to enhance the product capabilities (e.g., a systems starting point). No matter what the initial motivation for innovation, designers should consider the ripple effects, such as changes to the manufacturing process, the chemicals present in the final product, product performance, and product disposal. We have provided a detailed example of this iterative thinking in the Supporting Information using sunscreen as an example product. Teaching students to intentionally integrate systems thinking with green chemistry and life cycle thinking provides a structure for helping to ensure that their sustainable solutions are carefully considered and have a net benefit.

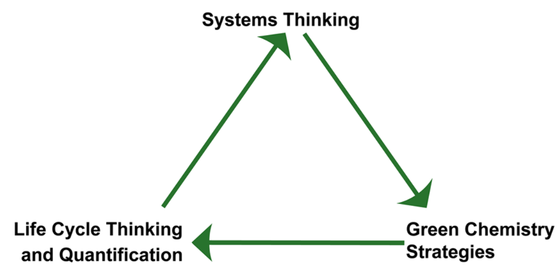

Figure 2. Interplay among the three lenses introduced in Figure 1: green chemistry, life cycle thinking, and systems thinking. Innovation can start with a possible green chemistry strategy, which is then assessed through life cycle analysis and further evaluated from a systems perspective. On the other hand, the process can be initiated by the recognition of a significant life cycle impact or a new insight provided by systems thinking. Regardless of the starting point, multiple iterations are needed to identify the best strategies to reduce life cycle impacts, improve performance, and gain leverage within the system.

■ OVERVIEW AND IMPACT OF WORKSHOPS

We developed a series of workshops to provide students with practical experience uniting green chemistry, life cycle thinking, and systems thinking to address an industrially relevant problem. Students were challenged to identify sustainable improvements or alternatives to a specific product under constraints related to product performance and viability. To test this approach, we piloted this project with an eco-friendly start-up company, WAYB. WAYB aims to create next-generation children's products that have improved product performance and reduced environmental and health impacts. The project was carried out in within the University of Oregon's Knight Campus Internship Program's[20] polymer track, which engages master's students in an intensive immersion lab wherein they work in small teams to solve real-world problems. The challenge for the student team was to design a more environmentally conscious car seat for infants. The initial goal was to identify a greener polymer foam to replace the expanded polystyrene (EPS) used in a car seat, but as the project developed, WAYB and the project team broadened the goal to greening all aspects of the product.

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On the basis of the results from this project, we found that a series of three workshops was effective for introducing and implementing the tiered strategy shown in Figures 1 and 2. Although we focused on the foam used in an infant car seat, we envision this framework being suitable for evaluating other types of products wherein a sustainable alternative material can be compared to an industry standard. The workshops were initiated with a framing lecture and a short summary of the project goals. Students did independent reading to familiarize themselves with the materials that were being studied and worked as a group to develop hypotheses that could be tested experimentally or supported with relevant literature. The duration of each workshop was typically a few days, depending upon the workshop and the breadth of data collected; however, this can be tailored to the project and the student cohort. More information on the technical implementation, course format and timelines are provided in the Supporting Information.

Figure 3 outlines the key components of each workshop and illustrates the crosstalk among them. Workshop I focused on life cycle thinking and assessing the impacts of a material of concern. The functional properties of that material were defined, tested, and compared with those of potential alternatives in Workshop II. In Workshop III, the students synthesized the results from the first two workshops to design and present sustainable alternatives and innovations. As described below, each workshop was developed in response to key sets of learning outcomes that addressed systems thinking, life cycle thinking, and green chemistry. The workshop format allows one to tailor the level of sophistication to different levels of student preparation, and we have suggested ways to adapt it to other student levels and venues.

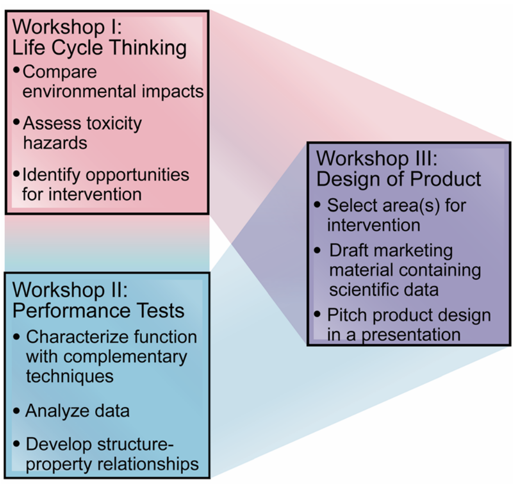

Figure 3. Summary of workshop activities. Workshops I and II involved literature research and data collection; this knowledge then informed Workshop III, where students moved forward to design and pitch their product.

Within our student cohort, these workshops were used to evaluate expanded polystyrene (EPS), which is the industry standard for high-impact absorbing materials in consumer products, and compare it with potential alternative foams.[21] In Workshop I, students used life cycle assessments to document the life cycle impacts of EPS. In Workshop II, students defined functional needs and evaluated the performance of alternative foams by characterizing their relative energy dissipation ability and rigidity. Using data from Workshops I and II, students worked in small teams to evaluate alternative approaches and develop mock-product designs and marketing materials in Workshop III. The marketing material consisted of communications to the public as well as a verbal pitch to all the participants in the class. Workshop III required the students to use systems thinking as they considered how to design a next-generation car seat that does not compromise child safety, is more environmentally friendly, and has attributes that can be communicated to consumers in a compelling manner.

After the conclusion of the course, students reported that they were drawn to this lab project because they felt it provided an experience that better prepared them to solve real-world problems. Students noted that this project was unusual because rather than having one correct solution, there were many potential solutions that had to be quickly assessed to determine which one was the most feasible and compelling. The students said this decision-making process aided in their development as independent scientists. They also reported that the project forced them to work in teams in new ways. Although they had worked in teams before, those experiences consisted mostly of dividing up the responsibilities from a given set of tasks. Here, the interdisciplinary nature of the project motivated the students to discuss how to best utilize each team member's expertise and undergraduate background. Finally, this lab was different from other teaching laboratories because they ultimately had to make conclusive decisions even though they did not have all of the information they might have wanted.

Students reported that the experiential learning they engaged in during this project gave them a significantly improved appreciation for the importance of life cycle and systems thinking. This project taught students that starting with green chemistry principles is helpful, but you have to look beyond that to assess the practicality of a solution. One student specifically noted that despite being trained in environmental chemistry, she still found green washing[6] hard to discern, and this type of project offered her a new way to critically analyze green claims. Students said that it was both frustrating and enlightening to get first-hand experience dealing with an interconnected system, where changing one element to be greener usually altered something else. They said learning that there will inherently be trade-offs but that there are ways to anticipate these and think systematically about them gave them strategies for implementing sustainable solutions in their future careers.

In evaluations conducted a few months after the students began working in industry, students reported that the problem-solving and material and time constraints that they experienced during the project prepared them for their current positions in ways that past teaching laboratories did not. The car seat application was especially constraining because the final product itself had safety requirements that needed to be addressed, including the use of child-safe materials and the necessity of passing a crash test. By working within these constraints, students discovered nonobvious leverage points, such as the foam manufacturing process.[22,23] Feedback provided by students is included in the Supporting Information.

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IMPLEMENTATION OF WORKSHOPS

Workshop I. Life Cycle and Toxicity Analysis of the Material of Concern: Evaluating the Environmental Impact of EPS

The purpose of this first workshop was to familiarize students with life cycle and toxicity assessments and to give students practice comparing impacts for a specific material of interest. It was important to begin the project with life cycle thinking because it gave students the tools to evaluate and compare alternative materials in Workshop III. Students performed individual research to learn about the production and life cycle of the industry standard, EPS; then, they combined their findings as a group to generate a summary document of the life cycle impacts. Students began by searching the primary literature for information regarding the production of EPS[24] and noting impacts at each stage of an EPS-based car seat's life. In the Supporting Information, we have provided a template for structured life cycle thinking that can be used to guide this process. Students worked together in class to discuss their findings and generate a group summary document. One effective way to do this is to have students use sticky notes to collaboratively develop a master life cycle summary on poster boards. Using the summary, students identified leverage points for improving greenness and weighed the pros and cons of innovating at various points. Students were directed to discuss ways to green the car seat in a scenario where they *could* replace EPS with a greener alternative foam and in a scenario where they *could not* replace EPS. Students also found articles on EPS toxicity and concluded that under normal use conditions, there are not any notable toxicity concerns for EPS use in a car seat.[25,26] Because it was determined that EPS did not have any major toxicity concerns, the students focused more on the life cycle impacts when thinking about opportunities for innovation; however, if future cohorts of students study other materials that do have toxicity concerns, then the toxicity reports would be more heavily emphasized.

After completing this workshop, students were familiar with using life cycle assessments and toxicity reports to identify and compare the environmental impacts of materials. For instance, students found that the negative environmental impacts of EPS are primarily due to its petroleum-based raw ingredients,[7] organic blowing agents,[24] and poor reusability and recyclability.[24,27] Students noted that there are existing alternative foams that may be able to mitigate some of these impacts. However, the impacts of an alternative foam would also need to be assessed, because it is likely that there would be some trade-offs. For example, although it is tempting to recommend a biopolymer, students found that biopolymers can actually have higher impacts than petroleum-sourced polymers in most major categories, including ozone depletion, acidification, eutrophication, carcinogens, and ecotoxicity.[7,28] This workshop also allowed students to identify areas for innovation that did not require replacing EPS, like the employment of a green blowing agent,[29] finding a secondary use for cracked or fatigued EPS, or reducing energy expenditure during foam shipping. Although EPS is not a toxicity concern because of its high MW and stability, the residual monomer could be hazardous.[25,26] Testing of monomer leaching or off-gassing was noted as a potentially useful future research pursuit.

Although our students evaluated EPS in this workshop, the approach can be easily tailored to examine other chemicals or materials of concern. Additionally, the scope and sophistication of this workshop can be adapted for other types of courses. For a lower-level course, instead of constructing a master life cycle summary, the instructor could give a lecture on what a life cycle assessment is. During this lecture, there could be a class discussion on how public perception of a material may not accurately reflect the life cycle impacts, and the instructor could guide students to consider hidden impacts encountered during production or transportation stages.

Workshop II. Defining and Measuring Performance: Evaluating Alternative Foams in a Simulated Crash Test

The purpose of this workshop is to compare the ability of an industry standard against potential alternatives that perform the key function of interest. We wanted to assess how EPS performed relative to other foam alternatives in protecting a child during a car crash. We challenged the students to compare the industrial performance of the materials on a benchtop scale without the need for specialized equipment. Because EPS has been the gold standard high-impact absorbing polymer foam for decades,[21,24,30−32] we used it as a point of reference during this workshop. Prior to beginning the lab work, alternatives to the industry standard material were acquired. In our case we worked with our industry partner, WAYB, to source specific alternative polymer foams of interest, but future cohorts can use any foams they think would be interesting to study. The results from one class can be used to inform the next class' selection so that each succession of this project allows for improved materials to be studied.

The students determined that they could simulate a small-scale crash test in lab by measuring a foam's ability to dissipate impact energy. Two experiments were performed to measure this: one ranked the foams' effectivity at absorbing instantaneous impact energy, and the other quantitatively characterized the foams' stress responses to incremental increases in strain. To study a foam's response to instantaneous stress, ping pong balls and baseballs were dropped on a foam, and the resulting ball bounce height was measured. The foams were ranked against one another to understand their relative energy dissipating abilities under low impact and high impact collisions.

Table 1 lists a summary of the results from this experiment. The materials were ranked from best (1) to worst (6) in terms of impact absorption on the basis of the ball rebound height (low height equals high absorption). The ping pong ball was dropped from a height of 1 ft, and the baseball was dropped from a height of 2 ft. Note that Alternative #1 could not be tested in this way because of the limited sample size. The students visually examined each foam before and after impact and noted any changes in appearance. They then discussed

Table 1. Student-Generated Data Ranking Foam Effectivity at Energy Dissipation from Instantaneous Impact[a]

Rank	Ping Pong Ball Bounce Dissipation Rank	Baseball Bounce Dissipation Rank
1 (best)	Alternative #5	Alternative #6
2	Alternative #6	EPS
3	Alternative #4	Alternative #3
4	Alternative #3	Alternative #5
5	EPS	Alternative #2
6 (worst)	Alternative #2	Alternative #4

[a]Alternative #1 was not included in this test because of the limited supply of this material.

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different mechanisms of energy dissipation[33] that may be occurring in each case on the basis of the foam performance and deformations (when applicable).

These tests allowed students to relate material structure to performance in a simulated commercial function. It is interesting to note that under low impacts, simulated with the ping pong ball, EPS did not dissipate very much energy, and it ranked #5 in performance, but at higher impacts, it moved up to #2. On the basis of the rankings of the foams and the observed damage, students hypothesized that at low impacts, the primary mechanism of energy dissipation is compression. The foams with macroscopically open web-like structures (as opposed to foams with closed discrete beads) performed well in these tests. However, at high impacts, these foams likely reached a threshold of energy dissipation after full compression, and thus they were not as effective. This hypothesis was supported by an absence of physical deformation for those foams. In contrast, the foams that had a beaded structure that could be crushed, such as EPS, were very effective at energy dissipation under sudden high impacts. Students hypothesized that as the foam beads displace air and irreversibly deform, they dissipate a substantial amount of energy,[33] thereby surpassing the nonbeaded foam performance under high impact.

Students recognized that an important quality of safe foams is that they are neither too rigid nor too soft. Foams that exerted high stresses under low strains were said to be too rigid and provided minimal elastic storage of impact force, whereas foams that exerted small stresses at high strains were said to be too readily deformable and provide weak structural and conformational strength. First, qualitative descriptions of each foam's rigidity were recorded including details such as foam's response to a fingernail scratch. Foam rigidity was then measured with an INSTRON 4444, a mechanical testing instrument, to generate stress versus strain plots (representative results shown in Figure 4).

In this workshop, the primary learning outcome was for students to learn how to evaluate the performances of alternative materials and relate the structural properties to the material function. Students characterized the rigid response and impact dissipation of alternative foams. They found that high rigidity and low dissipation ability were often related and hypothesized that this was because rigid materials were unable to cushion impacts effectively compared with more flexible materials. Students concluded that the best performing materials had moderate rigidity at low strain and readily deformed under high stress. This unique behavior was recognized in Figure 4 by the characteristic inflection observed at around 15% strain for EPS, Alternative #3, and Alternative #6.

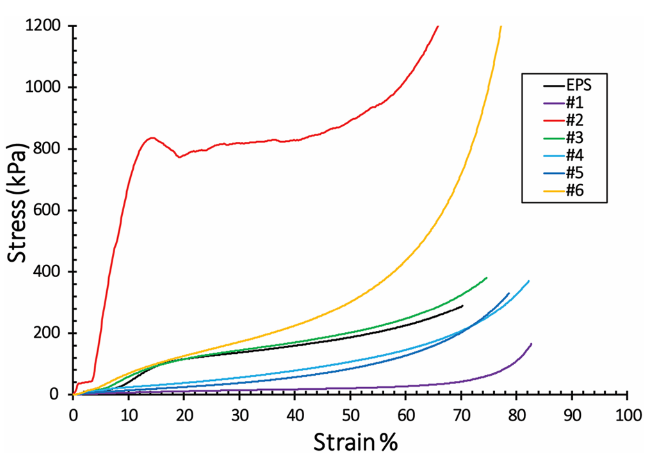

Figure 4. Student-generated data on foam rigidity. The graph depicts the stress−strain relationship of each of the alternative foam samples under quasistatic compression at room temperature, compared with that of EPS.

The details of this workshop can be tailored to the material of interest, the level of preparation of the students, and the time available. Although the stress versus strain plots are helpful for mathematically ranking the foams, these results generally agreed with qualitative observations of rigidity and could be omitted for a lower-level class or a more time constrained course. Additional metrics of material performance could also be included to scale the depth of this workshop. For example, under constant loading, foams can deform or fatigue irreversibly over time.[32] To measure how EPS deformation compared with that of alternatives, students compressed all of the foams a uniform amount with a mechanical testing instrument and then let the foams conformationally equilibrate overnight. The foams were initially cut into 13 mm blocks and compressed to 4 mm; then, the following day they were remeasured to determine the extent of irreversible deformation. The results of this study correlated with the qualitative observations from the high impact ball drops: the foams that were irreversibly damaged from the baseball drop also experienced a loss in thickness.

Workshop III. Design of a Greener Product: Proposed Infant Car Seat Design with Reduced Environmental Impact and Uncompromised Safety

The final workshop synthesized findings from Workshops I and II into a proposed product design with scientific and business merits. Students worked in small groups to decide how they wanted to innovate upon the basis of the life cycle impacts of the current industry standard, the performance of alternative materials, and the identified leverage points. Students developed a final presentation to present to the class, assuming the audience was composed of company stakeholders with a scientific background. Our students communicated directly with representatives at WAYB to advise on the marketing strategy for their innovation. In lieu of an industry partner, students could design accompanying marketing communications that articulate the strategy and benefits of their innovation to general consumers.

Following the collection of experimental data, students generated a shared databank that everyone in the class had access to. They then worked in small groups to discuss whether they should use one of the EPS alternatives or use EPS and decrease the environmental impacts by innovating at a stage of EPS's life cycle. If we refer to Figure 1 and the multiple lenses for inspiring innovation, replacing EPS with a safer alternative represents a change that starts in green chemistry principles, from which students then work outward to evaluate the alternative more comprehensively. Alternatively, starting by examining the life cycle of EPS to identify a place for improvement represents a midlevel starting point. Because of course constraints, the students did not have a chance to explore a third option: starting at the outermost lens and asking if there are other nontraditional ways to achieve the system goals. For example, removing the foam and reengineering a car seat's structure to achieve a new

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mechanism of energy dissipation would represent a change that starts from the system level. Achieving the same system goal by changing the mindset about how to do so represents a fundamental change in the system and is known as a *paradigm shift*.[19] Even if students do not have the time or expertise to explore redesign of a product entirely, we recommend a class discussion on what a paradigm shift would look like for a given product and how transformative this kind of systematic solution could be.

Once students decided on a product design, they prepared a 20 min presentation for the class, justifying their proposal with data from Workshops I and II that supported the likely success of the product. These supporting data included a discussion on which green chemistry principles were satisfied, what impacts were expected to be improved at a particular stage of the life cycle, and any expected changes in the performance of the product. To help students prepare a marketing strategy, they were shown examples of marketing material for real-world green products that used scientific data to articulate claims to consumers (examples are provided in the Supporting Information). We recommend having students either write a company blog post or design a marketing pamphlet to practice communicating scientific concepts to a general audience. Either of these formats would encourage students to use illustrations, graphics, photographs, and data to support their reasoning.

In this workshop, students learned how to use systems thinking to navigate the decision-making process around the selection of chemical and material alternatives. Students found that if they had prioritized green principles, they would have selected Alternative #3 to replace EPS because it has better reusability. However, a systems approach made students aware that the results of the impact analysis had to be prioritized over the green principles, and because EPS slightly outperformed Alternative #3 at high impacts, students ultimately decided that had to be prioritized. They ended up recommending modifying EPS production to eliminate the use of organic blowing agents and educating consumers on the hidden impacts of foam blowing agents. Additionally, they recommended exploring the performance of composite EPS foams in the future, with the hope that this may allow for the total amount of EPS to be reduced. In this decision making process, students experienced the importance of fully evaluating how a material replacement affects product performance, which led them to consider other possibilities for innovation, such as causing a life cycle change or creating a paradigm shift instead.

Studying a car seat was especially effective for teaching students to consider material performance because the students understood any car seat is going to have to pass regulatory safety testing before going on the market. Depending upon the foam alternatives selected for testing, the future outcomes of this workshop will vary, but in all cases, students should learn that systems thinking is needed to design a next-generation product that is better from both an environmental and performance perspective. Although we did not identify a material that significantly outperformed EPS for car seat safety, we only selected six alternative foams to test for this pilot lab. We expect that future student cohorts could use these initial findings to tailor the selection of alternatives to identify higher performing foams, and each successive round of implementation of this project would allow for a more informed selection of materials for testing. Moreover, even for a set of materials with subpar performance, we could have asked students to identify an alternative application where it would make sense to switch from EPS to one of the tested alternatives. For example, we expect that some of the alternatives would have offered sufficient impact absorbance for package padding material, with an improved end-of-life outcome over that of EPS.

This final workshop can also be easily adapted for lower-level or shorter courses. For a short and easily accessible version of Workshop III, students could work in groups to identify their most promising material(s) on the basis of the data from prior workshops. They would then individually describe their selection and the benefits of it in a postlab write-up. If the original industry standard material is selected, they should describe why they chose to keep it and how they could still meet the company goal to green their product. To practice articulating the benefits of a product to consumers, the students could also design a new product label that accurately communicates both a green and functional advantage of this product. Workshop III also provides an opportunity for implementing a systems thinking project in a lecture course without a lab. An instructor could provide students with a summary of life cycle impacts, toxicity, and performance measurements (i.e., the data that would be gathered during Workshops I and II) and students could use this information to perform Workshop III.

■ FINDINGS AND FUTURE OUTLOOK

Herein, we have described an approach where students work at the interface of innovation, environmental stewardship and chemistry to design a next-generation car seat. This project was developed with industry partners to provide an immersive learning experience for students that brings together tools from green chemistry, life cycle thinking, and systems thinking. By considering both the environmental impacts of a polymer foam and measuring the functional properties, students practiced using their chemistry toolbox for sustainable innovation. The project components were divided into three workshops, with each emphasizing different learning outcomes (detailed in the Supporting Information). In Workshop I students learned how to evaluate the greenness of a foam by engaging in structured life cycle thinking and using EPS as the model foam. Workshop II focused on functional performance. The students found that the ability of a foam to compress is one approach to dissipate energy, but it is not the major mechanism under high impact conditions. Additional mechanisms, such as irreversible foam deformation, are needed.[33] This knowledge was then built upon when students observed that irreversible deformation is desirable at high impacts but not with the low impacts encountered during routine wear and tear. Finally, in Workshop III, students synthesized their knowledge from Workshops I and II to make a recommendation on the product design with the best performance and most reduced impacts. After integrating their learnings from green chemistry, life cycle thinking, and systems thinking, students developed and optimized their proposed solutions and practiced marketing their alternative to both nonscientific and scientific audiences.

These workshops have been intentionally designed to be flexible and adaptable for other contexts. While this project is written with senior-level chemistry undergraduates or starting graduate students in mind, the workshops can be tailored depending on the specific course and allotted time. Within each workshop, we have included suggested methods of modifying the sophistication. For example, in Workshop II the

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material evaluation can range from methodically quantitative, through the use of polymer characterization techniques, to rudimentary qualitative rankings determined with ball drops and visual observations. Beyond tailoring the sophistication of these three specific workshops, we see this format as a portable framework for inspiring other systematic product evaluations. In all cases there would be a workshop focusing on material impacts (both biological and environmental), a workshop focused on comparing relevant performance metrics, and a marketing workshop where students communicate their innovation. Other suitable product candidates that we envision fitting well within this framework include food packaging, house paint, cooking skillets, and baby bottles. No matter the product of interest, the larger purpose of this framework is to help students develop a fluency in systems thinking that transfers to future endeavors.

We have found that the increasing visibility of green products has made students interested in sustainable design, but they are often lacking experience developing the technical implementation. To complement the widespread incorporation of green chemistry into many undergraduate chemistry curriculums, it is important to give students opportunities to practice using these principles to problem-solve (as opposed to just performing green laboratories). Having scientists that are trained this way is vital for green chemistry's successful adaptation outside of academia.[34] The cohort of master's students who participated in this lab noted that this was their first experience using green principles to address a problem when the solution was not provided, despite coming from a range of undergraduate universities with differing bachelor's degrees.

A key benefit of this project is that students begin to develop a habitual state of mind for using systems thinking when approaching green product design. Using a systems approach means that students are aware that green principles can be used to make irresponsible choices if too much attention is paid to only one piece of a puzzle.[8] We have found that this reductionist thinking is common when students are tasked with evaluating chemical sustainability. Students are likely to begin this project with an emphasized caution against EPS because of its well-known end-of-life impacts. However, after evaluating functional attributes in tandem with life cycle impacts, students are faced with tough systems decisions without an obviously correct answer; any innovation will have a benefit and associated side-effects, and the students must decide how they can maximize the cost−benefit ratio. The marketing portion of this project gives students an opportunity to practice communicating sustainable design across disciplines, a key component of systems thinking training.[8] After completing this lab, students report feeling empowered to strive for sustainable product design that advances past vague buzzwords to substantiated claims of environmental stewardship and superior functionality. Because of the inherent complexity and vagueness of systems thinking, we have observed that students need these types of hands-on immersive exercises to develop an intuition for thinking in systems. We hope that this project inspires others to design activities or courses where students are not just exposed to the benefits of green chemistry but get to experience coming up with their own practical ways of implementing green chemistry. Successful, widespread implementation of green chemistry in commerce demands a systems thinking approach to design in which both environmental impacts and product performance are weighed. It is up to educators to give the next generation of scientists the tools to do this.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00336.

> Student feedback, structured life cycle thinking template, learning outcomes, details on workshop implementation, resources for introducing students to green marketing, and specific example of the iterative thinking shown in Figure 2 (PDF)

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Notes

The authors declare no competing financial interest.

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