Incorporating Elements of Green and Sustainable Chemistry in General Chemistry via Systems Thinking

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Abstract:
Ideas related to green and sustainable chemistry are important components for helping students connect chemistry knowledge they acquire to larger understandings of the world. Given the importance of general chemistry in the college level curriculum of many science majors, the ability to add concepts related to sustainability represents an important opportunity for educators. This goal must be accomplished, however, while bearing in mind that foundational knowledge about chemistry remains the core responsibility of the general chemistry course. By finding aspects of the traditional chemistry content curriculum that connect to earth and societal sustainability issues via the concept of planetary boundaries, general chemistry can provide both key learning opportunities. Students can gain required core understanding and simultaneously improve their ability to connect those foundational concepts to larger sustainability issues. Examples of how this teaching strategy can be implemented and assessed are reported.

Key Words
systems thinking, curriculum development, sustainability, rich context, general chemistry

Introduction

The role of introductory college science courses, including general chemistry, has long been defined in terms of fundamental concepts that students need to know to proceed to subsequent courses. While this core component is unlikely to be entirely replaced, recent developments in understanding how people learn [ref 1,2] suggest that explicitly helping students to transfer fundamental knowledge to broader topics is a key aspect for teaching and learning in Science, Technology, Engineering and Math (STEM). The challenge becomes, therefore, how to infuse a course, such as general chemistry, with enough connections to broader themes and skills to allow students to transfer knowledge while maintaining appropriate attention on fundamental concepts.

The approach suggested here is that having an organizing theme that connects fundamental concepts in chemistry to the framework of planetary boundaries [ref 3-5] and uses concepts associated with systems thinking [ref 6]. This choice represents an
excellent method for accomplishing the balance between core concepts and their application to sustainability, in terms of earth and societal systems.

Systems thinking has emerged as an important component of recent efforts to enhance STEM education. In particular, at the K-12 level in the United States, the *Next Generation Science Standards (NGSS)* include systems thinking and modeling as a cross-cutting concept. [ref 7] There are a number of definitions for the application of systems thinking in educational settings. [ref 8-10] These definitions are similar but not clearly equivalent. As may be inferred from the existence of multiple definitions of systems thinking in education, there has been significant effort applied to the incorporation of these ideas in various disciplines, but less so within chemistry. For example, a recent review emphasizes educational developments in biology, engineering, environmental science and geosciences, in enumerating systems thinking work. [ref 11] Despite this emphasis, however, there are topics where efforts in other fields clearly touch on topics in general chemistry, such as the water cycle and water usage. [ref 8,12] One additional challenge lies in providing meaningful assessment instruments, in addition to pedagogical interventions designed to enhance students’ systems thinking. [ref 13]

To advance the discussion of incorporation of systems thinking attributes in general chemistry it is helpful to consider those described by Assaraf & Orion [ref 8] in their description of systems thinking in the context of geosciences education. These authors have enumerated a set of eight traits that characterize systems thinking, including: (1) the ability to identify the components of a system and the processes within the system; (2) the ability to identify dynamic relationships among the system components; (3) the ability to identify dynamics relationships within the system; (4) the ability to organize the systems’ components and processes within a framework of relationships; (5) the ability to understand the cyclic nature of many systems; (6) the ability to make generalizations; (7) understanding the hidden dimensions of the system; (8) thinking temporally, including retrospect and prediction. These attributes can serve as a foundation by which core chemistry knowledge is connected to issues of sustainability, and thus allow the incorporation of both systems thinking and sustainability in general chemistry.

Another important aspect of how systems thinking can be implemented into general chemistry arises by using a systems framework lies to question the appropriateness of boundaries that are considered. Thus, in addition to other attributes, systems thinking provides impetus to ask the question: are we considering the right boundary for this process? [ref 14] This is a powerful way to shape student attitudes towards core chemistry knowledge from a reductionist view towards a more expansive one that includes applications of that core knowledge [ref 15]. One example is the idea that chemicals may have both benefits and hazards, and those aspects require consideration of what the system is that boundary. [ref 16]

Green chemistry has substantial overlap with the types of reasoning that make up the central aspects of systems thinking as well. For example, the ability to conduct life cycle assessment [ref 17] in the creation of products, such as textiles [ref 18] includes aspects of systems thinking. [ref 19] Most reports of the incorporation of green chemistry
concepts in introductory chemistry, however, have placed their focus on the laboratory, often with an emphasis on chemical waste reduction as a key driver [ref 20-22]. Nonetheless, the design principles of green chemistry are ideal vehicles to help students ask the question of what boundary should be used in thinking about a chemical process. In particular, the idea of asking where the materials that are present as reactants are created often provides an entryway into a more systems thinking approach to understanding fundamental chemistry ideas.

Beyond green chemistry and the design principles for which it is best known, the concept of infusing sustainability more broadly also shows appeal to many students. A challenge here lies in the often-noted tendency to require multidisciplinary approaches to sustainability courses. [ref 23] Even so, with its historical moniker as the “Central Science”, chemistry classes are well-placed to incorporate connections to other disciplines by incorporating explanations of chemical issues within rich contexts. [ref 24-26] While much work has been put forward within the framework of rich contexts, the ability to use an overarching organizational principle for viewing sustainability adds a new, and helpful dimension to this style of educational intervention in chemistry classes.

**Planetary Boundaries**
The key concept that provides the overall framework discussed here and allows for the connection of systems thinking to sustainability is planetary boundaries [ref 3-5]. While concerns have been noted for this concept [ref 27] it provides an important route for thinking of both components and larger systems. This framework is particularly helpful in the context of applying systems thinking in general chemistry. The central concept of planetary boundaries is to take available estimates of global scale issues and assess whether or not a sustainability “tipping point” has been surpassed due to human activities. Figure 1 provides a representation of planetary boundaries that is useful in emphasizing the role of chemistry, including concepts taught in general chemistry, in understanding planetary boundaries.
In this figure, the horizontal bar represents the putative tipping point for the characteristic, and those systems that are below it and in red tones have already surpassed the probable tipping point. Using this representation consistently in class to connect various foundational chemistry topics to the idea of sustainability carries the memorable tag-line for students, “Does this chemistry help us understand whether we are above the bar or not?” In some cases, chemical pollutants and atmospheric aerosols specifically, insufficient data is available to make an estimate. Finally, characteristics that remain above the line and in shades of green have not yet reached an estimated tipping point. Original reports [ref 3-5] included numerical estimates as percentages toward the tipping point, but as an organizational framework such detail is not required, and could be counterproductive in the context of general chemistry where some aspects of the planetary boundaries issues are beyond the scope of the science content of the course. One reason this framework works so well for infusing elements of systems thinking into general chemistry lies in the fact that most of the areas of key concerns have significant chemical aspects associated with them. Both areas where estimates cannot yet be made involve chemistry, and this fact emphasizes how furthering knowledge and research in chemistry is important for devising appropriate approaches to issues related to sustainability. Further, the issues of biogeochemical flows and climate change, which are estimated to have surpassed a tipping point, also clearly involve chemistry as both a source for the current concern, and quite likely as a component of any solutions that can be developed to address the problems. This chapter will describe several examples of how this is done in one particular general chemistry course.
Considerations of Course Design

When devising interventions that allow instruction to highlight issues related to sustainability, it is vitally important to acknowledge and account for constraints associated with the larger curricular context of the course. This idea is particularly true for a “gateway course” such as general chemistry that is required for a large number of college degrees in the sciences. Thus, curricular innovations undertaken in this course are not that similar to what might be accomplished in a dedicated, inter-disciplinary course, for example. [ref 23] There are undoubtedly many ways that this type of consideration can be accounted for, but our approach emphasizes incorporating ideas related to sustainability in the chemistry course objectives. [ref 28, 29] Communication with students that articulates outcomes they perceive they can achieve represents an important aspect of successful teaching and course improvement. [ref 30] So, while the core content knowledge to be covered in a general chemistry course is vital to maintain and emphasize, adding systems thinking objectives must also be clearly communicated and connected to the larger goals for student learning in the course.

In chemistry education over the past several years, efforts led by the American Chemical Society Examinations Institute (ACS-EI) have been mapping the four-year curriculum in terms of anchoring concepts or “big ideas”. [ref 31-33] This tool, called the Anchoring Concept Content Map (ACCM), has also been used to identify gaps in the traditional curriculum, particularly with respect to conceptual knowledge with applications in sciences outside of chemistry [ref 34] and results of this process for only the first semester of general chemistry are depicted in Figure 2.
ACS Exams are produced by committees of instructors from across the US, and tend to reflect content coverage more succinctly than textbooks, which routinely include more topics than any instructor teaches. This histogram, therefore, represents a reasonable...
estimate of what topics are considered important in the curriculum, and it reveals information both in terms of topics that appear often, as well as those that are seldom tested. The incorporation of sustainability content and systems thinking needs to be accomplished without dramatically changing this content coverage. Ideally, therefore, incorporation of these newer ideas would be accomplished within areas that already provide important focus for the course.

Given this premise, areas that have been emphasized over the past 20 years in the first semester course include; atomic structure, VSEPR to assign molecular shape, relative strength of intermolecular forces (IMF), physical properties and gases, balancing chemical equations and categorizing reactions, stoichiometry and limiting reactants, energy and thermochemistry. While connecting with these key topics represents one way to address potential concerns about taking time to include sustainability and systems thinking, it’s also worth noting areas that have not been part of content coverage over the years. For example, as was noted previously, [ref 34] despite having a large clientele interested in the life sciences, general chemistry has not been very adept at including non-covalent forces within larger biomolecular systems in the coverage of IMF. There are also important ideas that have garnered little enough attention that they don’t even appear in the ACCM itself. One noteworthy example of this is that toxicological ideas, including toxicity and exposure, are not present in either version of the General Chemistry ACCM [ref 31, 32], despite the importance of this idea in a number of fields and in the manner in which chemistry affects society. Indeed, the role of toxicity is incorporated into the first day of class in our model, as a core component of understanding the risk/benefit analysis of chemical systems.

In addition to this overview of content, it is also important to note that the textbook is often the primary artifact that guides curriculum. Most general chemistry courses, particularly those with multiple sections taught by different instructors, tend to follow the chapter organization of textbooks. The first semester course where systems thinking components were added follows this pattern as well, with the chronological order of topics as follows:

1. Introduction, particles and matter  
   a. Includes units of measure
2. Atoms, ions and molecules  
   a. Includes initial introduction to the periodic table, nucleosynthesis and isotopes
3. Stoichiometry
4. Aqueous reactions / water chemistry
5. Thermochemistry
6. Gases and their properties
7. Quantum model of atoms and atomic structure  
   a. Includes periodicity
8. Chemical bonding
9. Molecular geometry
10. Intermolecular Forces  
    a. Includes liquids and physical properties of liquids
This general ordering needs to be maintained in a multiple-section teaching environment, so our efforts to infuse sustainability are accomplished within this broad outline. Because the overall outline is maintained, there are inherent time constraints on the amount of material that can be introduced to support student awareness of systems thinking.

**Incorporation of Sustainability and Systems Thinking**

The commitment of time to coordinating sustainability concepts in general chemistry begins on day 1 of the course. Noting the explicit learning outcomes that connect foundational concepts to applications of earth and societal systems represents a vital part of the first day activities. This includes the initial presentation of the concept of planetary boundaries as depicted earlier in Figure 1.

The initial instance with the introduction of new, broader context ideas that can be related to systems thinking arises when the periodic table is first introduced in the second content area. At this time, we include the concept of ranges of atomic weights present in the most recent IUPAC approved periodic table. [ref 35] At this early point, the connection to climate change and evidence related to it is only mentioned, and connected to the planetary boundaries construct, without any details. Rather, it is noted that later in the course, the idea that isotopic abundance can vary in nature leads to an ability to estimate “deep time” in ice cores will be an important idea in understanding the evidence about climate. Similarly, in the 3rd topic area, stoichiometry, we include an emphasis on the reaction of nitrogen and hydrogen to form ammonia. This reaction is used as the key example for the description of particulate nature of matter (PNOM) diagrams [ref 36] within stoichiometry, for example. These early additions are essentially examples that both advance the core content and foreshadow the role that foundational chemistry knowledge plays in understanding planetary boundaries.

The first time when issues related to planetary boundaries arises in a way that can strongly motivate the chemistry covered arises in the fourth topic area – water chemistry. This instance of incorporating systems thinking has been described in greater detail elsewhere [ref 37], but it centers around biogeochemical flows, particularly of nitrogen. Because Iowa State is located in an agricultural region of the US, the large-scale application of nitrogen-based fertilizer represents a local issue in addition to being part of a larger, planetary boundary content area. These characteristics, however, play an important role in implementing the concept of exploring boundaries as a way to introduce systems thinking concepts.

In this case, the foundational chemistry concept is solubility and solubility rules. Solubility rules are routinely a source of consternation for students, in part because they seem to arise from arbitrary lines drawn along a continuum of solubility [ref 38] and partly because they seem rather compact and used for a small portion of the curriculum. The primary way students are accustomed to interacting with solubility rules lies in assessments that ask, “which pair of solutions, when mixed, will form a precipitate?” so that the rules are pointedly oriented towards a laboratory oriented activity with little relevance to students outside of that activity.
Nonetheless, perhaps the most commonly remembered solubility rule is that all nitrates are soluble, and this allows the introduction of how nitrates, applied in fertilizers, enter the watershed. Because of this, local issues related to drinking water standards provide the first “expanded boundary” with solubility getting “out of the laboratory” and making a difference in how municipalities produce safe drinking water. Because this aspect of nitrates in rivers also incorporates standards for drinking water based on at-risk populations, specifically infants in this case, it also requires the further exploration of ideas of toxicology. [ref 39] Thus, taking a modest amount of time to situate solubility in a regional level environmental concern serves to highlight both systems thinking and aspects of green chemistry. Importantly, it also allows multiple connections to planetary boundaries if the boundaries being considered expand beyond the local, agricultural region. Specifically, the role of Midwestern agricultural practices on the creation of the hypoxic “dead zone” in the Gulf of Mexico becomes important if we ask, “what if thinking about nitrates in Iowa rivers is not a large enough boundary to consider?” This expanded boundary question invokes several connections to the planetary boundaries concepts depicted in Figure 1. Most recognizably, the connections to fresh water usage, and the importance of water treatment chemistries is readily noted. Perhaps less obvious, but equally important is the concept of land use changes. This idea is approached by noting the differences between historical land use patterns of tall-grass prairies in Iowa compared to modern row-crop plants. Finally, the chemical consequences of (i) nitrate loading into rivers, (ii) the flow of those nutrients to distant regions and (iii) their effects when they arrive there, show how larger scale systems thinking concepts are important. Just as important, however, is the ability to make the argument that beginning to understand the larger scale system is dependent on understanding the components of that systems – in this case the foundational chemistry concept of the role of solubility of nitrates in water.

Finally, one additional aspect of solution chemistry is introduced with the idea of foreshadowing in mind once again. Thus, the use of Beer’s Law to determine concentration of solutions that include absorbing solutes is covered. The ability to have the concept of $A = ebc$ and noting that the extinction coefficient, $e$, is dependent on the frequency of light being used will be used again when climate change is discussed.

The traditional ordering of chemistry topics, in terms of textbook chapters, may diverge a bit at this point in the course based on the specific book being used, but in our situation the next topic covered is thermochemistry. Because of the importance of the Haber-Bosch process and the role of energy in the fixing of atmospheric nitrogen, the biogeochemical flow of nitrogen can be further accentuated immediately following the treatment of water chemistry. This connection reinforces the systems thinking aspects by “expanding the boundary” in a new direction, one that is about the origin of the chemicals, rather than their fate in the environment.

These first examples of incorporating aspects of chemistry related to the biogeochemistry of nitrogen reflect an implementation strategy where the new content changes little about the traditional presentation of the content curriculum. In this specific case, the order of
topics in water chemistry and thermochemistry is largely unchanged, but examples are pulled from the rich context of nitrogen flow in the environment. This allows connections to planetary boundaries and sustainability, without taxing instructional resources. For example, teaching assistants were notified of the new material, but it didn’t take up much time from weekly staff meetings to get everybody up to speed.

When incorporating concepts related to climate change, however, both content additions and changes to customary ordering arise. These changes affect the coverage of gases and their properties the most. Where traditional coverage of this material emphasizes the sameness of ideal gases, such that a single equation is usable for many aspects of any such gas, to connect atmospheric gases to climate change requires a different approach. In addition, for a course at the university level, gas law applications and calculations seem quite familiar to many students from prior exposure to them in high school. This familiarity can lead to a decrease in attention and motivation for a large fraction of the students in a course, because they perceive their prior knowledge to be adequate to meet expectations for that particular content.

Thus, in the approach that connects to climate change, the chapter on gases begins with a direct connection to prior idea in the course, from the just covered chapter on energy. Thus, the connection between combustion, energy and the production of CO$_2$ is noted, and the question of what boundary needs to be considered leads to the temporal nature of the evidence, specifically how does science know anything about temperature and atmospheric composition over time. This question leads immediately to the concept of “deep time” [ref – 40] and ways to infer information about climate hundreds of thousands of years ago. Establishing the ability to measure concentrations of CO$_2$ over time is readily introduced in terms of bubbles trapped in the ice, but the measurement of temperature requires the return to the idea of isotopes and atomic weight. The difference between the movement of $^{16}$O water and $^{18}$O water because of the difference in mass fit well in the flow of the course because it is related to the concept of the Boltzmann Distribution, which is part of the coverage in the chapter on energy. That these ideas also connect to atmospheric dynamics, an important aspect of systems thinking is essentially a bonus for making the connections to systems thinking skills. Having used this concept to introduce the movement of gas molecules, the approach taken to cover this chapter is also changed. The content coverage begins with gas kinetic theory rather than the more traditional approach of describing historical observations of gas laws. This change has the effect of catching the attention of students who might otherwise be inclined to “coast” through previously seen gas law problems.

Once gas kinetic theory has been established, it is used to explain the historical gas laws, as is commonly done, but the question of boundaries is quickly introduced again. The hook used is to ask the boundary question in terms of what is gained and what is lost by treating all gases alike, which is the power of the ideal gas law. Nonetheless, it does not answer the key question of why CO$_2$ is a greenhouse gas, while neither N$_2$ nor O$_2$ are. This is the moment when we are able to connect most strongly to climate change as an area where a tipping point has been reached, by reintroducing Beer’s Law, which had
been included in the earlier work on solutions. In this context, the coverage focuses on both concentration and the extinction coefficient.

The concentration discussion emphasizes the changes in CO$_2$ in the atmosphere, including the concepts from the initial deep time discussion, but also invokes the isotopic abundance concepts to establish the anthropogenic nature of the added CO$_2$ since the dawn of the industrial revolution [ref 26]. Then the extinction coefficient discussion centers on what renders gas molecules capable of absorbing IR radiation. The relative simplicity of the molecules involved allows this discussion to occur prior to a detailed discussion of molecular shape, which is later in the course structure. Ultimately, the role of symmetry of different molecular vibrations is introduced as the key factor that makes the molecules different. This conversation does require students to come to terms with the idea that molecules vibrate. As has been noted in a previous study [ref 41] pre-instruction surveys found only 1/3 of the students in general chemistry classes are aware that molecules vibrate. After instruction based on the need to understand the role of molecular vibration in identifying greenhouse gases, however, correct student conceptual understanding of greenhouse gas vibrational motion exceeded 80%. What has been added since these earlier studies is the idea of linking the concept of molecular vibration to systems thinking by asking the question about the correct boundary. In this case, the expanded boundary is whether or not the ideal gas model, where the identity of the gas is not important, is enough to explain all properties of atmospheric gases that are important. Ultimately, N$_2$, O$_2$ and CO$_2$ all behave as ideal gases in the atmosphere, but more than the ideal gas model is needed to be able to understand key, larger-scale issues.

These examples are designed to highlight how green and sustainable chemistry concepts can be integrated in a coherent way as part of the general chemistry course. The coherence itself is provided in two ways. As noted in Figure 3, we first connect all of the content coverage modifications to the idea of planetary boundaries. Returning to the same construct, and focusing on only two aspects of that construct, allows students to build depth of understanding through a narrative of how chemistry affects broader scientific issues, rather than acting as a compartmentalized knowledge base. The other aspect of the coherence is the process by which we routinely engage with the broader context. Specifically, the repeated questioning of whether or not we need to consider broader boundaries for the science as we cover it becomes a familiar process, one that accentuates the need to make the broader connections.
Evaluating student learning of new, connected materials

While the implementation of teaching materials related to sustainability and systems thinking represents the core activity of the work reported here, it remains important to assess whether student learning arises from this intervention. There have been two key methods by which student learning has been ascertained in this project. First, when an appropriate concept inventory is available, it has been used. [ref 41]. Second, it is important for students to see questions about these more application-oriented topics on mid-term exams, or the assessments will not signal that the material is important. As such, the inclusion of items that query student understanding of these systems thinking
related applications becomes an important component of generating student buy-in to learning the material. Thus, while this evaluation of the teaching intervention has no control group (all students were exposed to the material and tested on it) the general impact of the learning can be put into the context of overall student performance in the chemistry course itself. There are two forms of evidence from assessments that have been undertaken in this teaching intervention, measuring conceptual understanding and direct testing of content knowledge in course exams.

The conceptual learning of climate change content acquired by students uses measures that have been reported previously as part of the description of the concept inventory instruments used to accomplish this assessment [ref 41]. The most important aspect of this prior work in terms of establishing efficacy of incorporating content related to planetary boundaries is the overall change in conceptual understanding in pre-/post-testing of climate change related concepts. For a sample of 128 students, the average percentage correct in the pre-test on the climate science concept inventory was 42% while the post-test was 77%. Thus, even with a rather modest level of instructional time dedicated to climate science related materials in the gas laws chapter, the gains in conceptual understanding are noteworthy.

For students to value the added content, assessments must include items related to that content. In large courses, assessment routinely requires the use of multiple choice questions, and in the case of incorporating sustainability items that test the concept should have psychometric parameters in line with other content in the course. This premise is confirmed for items that incorporate these themes as shown in Table 1.

Table 1: Comparison of Systems/Sustainability Items and Item Averages

<table>
<thead>
<tr>
<th>Item Topic</th>
<th>Percent Correct</th>
<th>Point Biserial</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cause of lead contamination in Flint, MI</td>
<td>84%</td>
<td>0.27</td>
</tr>
<tr>
<td>2. Soil biome and redox chemistry of nitrates</td>
<td>17%</td>
<td>0.24</td>
</tr>
<tr>
<td>3. Large components of the natural carbon cycle</td>
<td>65%</td>
<td>0.47</td>
</tr>
<tr>
<td>4. Small components of the natural carbon cycle</td>
<td>68%</td>
<td>0.26</td>
</tr>
<tr>
<td>5. Deep time and CO2 concentrations</td>
<td>75%</td>
<td>0.30</td>
</tr>
<tr>
<td>6. Deep time and temperature</td>
<td>36%</td>
<td>0.26</td>
</tr>
<tr>
<td>7. Vibrational motion of gases and IR radiation</td>
<td>84%</td>
<td>0.36</td>
</tr>
<tr>
<td>8. Relationship between IR absorption and greenhouse gases</td>
<td>66%</td>
<td>0.48</td>
</tr>
<tr>
<td>Average of all Multiple-Choice items</td>
<td>70%</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Looking at the information in Table 1, we see that 3 out of 8 items (3, 4 & 8) have percentages correct quite close to the average, 3 out of 8 items (1, 5 & 7) have percentages correct that are notably higher than the average, and 2 items (2 & 6) have percentages correct considerably lower than the average. In addition, the point-biserial correlation values for all eight items are positive (meaning students with higher test scores are more likely to answer correctly.) There are any number of arguments that have been advanced to establish guidelines for what constitutes a “good” point-biserial value. Values above 0.20 have been suggested as a standard that merits this distinction [ref 42],
and all of these items that test connections to planetary boundaries in the course exceed this standard. This is true even for items with very low or very high percentage correct values, which inherently have lower point-biserial values. This evidence does not prove that testing of concepts related to systems approaches to incorporate sustainability is inherently strong psychometrically, but rather that it is possible to write and incorporate such items in general chemistry tests and maintain good assessment characteristics.

**Discussion and Conclusions**

The premise of the intervention presented here is to make the argument that important advances in curriculum can be made while largely maintaining the traditional content coverage of general chemistry. By carefully choosing a small number of content areas related to planetary boundaries, students in first-year college chemistry courses can be encouraged to engage in several helpful learning opportunities. First, by routinely asking the question “am I using the correct boundary for understanding the role of this science?” students can be induced to move beyond compartmentalized strategies for science topic, such as those found in chemistry. Second, the concept of learning more complex systems by first considering foundational level components then connecting them to larger issues represents a style of scientific thinking that needs to be emphasized as people learn chemistry and its role in understanding the world around us. Third, the amount of time that needs to be used for this type of instruction, while non-zero, is not so large as to prevent a strong level of fundamental understanding of topics in the foundational courses. Finally, even though systems thinking and issues of sustainability are inherently complex topics, it is possible to both teach and assess these concepts in a meaningful way, even at the introductory level of college chemistry.

The examples offered here were clearly chosen with several aspects in mind. First, the connection to planetary boundaries provides a consistent, large context to which many students can relate. Second, there are several science (and specifically chemistry) components encompassed within planetary boundaries that mean an individual instructor can find content within the framework with which they are comfortable. This makes the overall strategy adaptable to the skills and capacity of many instructors. The examples provided here merely illustrate one path for such teaching strategies. Third, assessment efforts carried out with this particular implementation suggest that it is possible to introduce content in this way in a meaningful and measurable way in the general chemistry curriculum. Fourth, and finally, the introduction of concepts related to sustainability and connecting them to green chemistry principles provides not only useful content to those for whom general chemistry is their last class, it also allows an earlier time in the curriculum to introduce these concepts and paves the way for more inclusion of green chemistry in its more common curricular location of organic chemistry.
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