George M. Bodner[1]

The quadruple bottom line: the advantages of incorporating Green Chemistry into the undergraduate chemistry major

[1] Department of Chemistry, Purdue University, 560 Oval Drive, West Lafayette, IN 47907-2084, USA, E-mail: gmbodner@purdue.edu

Abstract:
When the author first became involved with the Green Chemistry movement, he noted that his colleagues in industry who were involved in one of the ACS Green Chemistry Institute® industrial roundtables emphasized the take-home message they described as the "triple bottom line." They noted that introducing Green Chemistry in industrial settings had economic, social, and environmental benefits. As someone who first went to school at age 5, and has been "going to school" most days for 65 years, it was easy for the author to see why introducing Green Chemistry into academics had similar beneficial effects within the context of economic, social and environmental domains at the college/university level. He was prepared to understand why faculty who had taught traditional courses often saw the advantage of incorporating Green Chemistry into the courses they teach. What was not as obvious is why students who were encountering chemistry for the first time were often equally passionate about the Green Chemistry movement. Recent attention has been paid, however, to a model that brings clarity to the hitherto vague term of "relevance" that might explain why integrating Green Chemistry into the undergraduate chemistry classroom can achieve a "quadruple bottom-line" for students because of potentially positive effects of adding a domain of "relevance" to the existing economic, social, and environmental domains.

Keywords: Green Chemistry, education, sustainability, Sustainable Development

DOI: 10.1515/psr-2017-0003

1 Introduction

This chapter will describe the effect of the Green Chemistry movement on those of us who devote a considerable amount of our professional careers to trying to improve the way we "teach chemistry," as opposed to recommendations in this volume about improving the way people "do chemistry." In doing so, it will trace the genesis of the Green Chemistry movement; differentiate between the concepts of Green Chemistry and Sustainability (or Sustainable Development); examine the philosophy upon which the incorporation of Green Chemistry into the chemistry curriculum might be based; and try to justify the author's belief that Green Chemistry not only can, but should, be incorporated into every chemistry course from students' first exposure in the K-12 classroom to the last graduate level course they take on the way to a Ph.D. in some aspect of what can be referred to as the "chemical enterprise."

2 The Green Chemistry movement as a community of practice

When a member of the ACS Board of Directors, the author was often been involved in discussions of why individuals become members of the Society. Access to "information" within the context of our journals, SciFinder and other products of the Chemical Abstract Service, and technical meetings/conferences were always high on the list. But it has been interesting to note that "opportunities to network" is toward the topped the list, as well.

A useful model for understanding the idea of networks of professionals working in a given sub-discipline or domain of the chemical enterprise might be the concept of "Community of Practice" [1], which can be defined as "… groups of people who share a concern, a set of problems, or a passion about a practice and who deepen

George M. Bodner is the corresponding author.

their knowledge and expertise by interacting on an ongoing basis" [2]. These groups often evolve through interactions that occur during professional discourse and collaboration and have the effect of making members of the community more effective as they share knowledge [3]. As anyone who works on research projects that involve either undergraduate or graduate students soon learns, experts in a discipline become more productive by helping/mentoring others [2]. Within the context of teaching/learning, students' grasp of both the content of their discipline and the process of reasoning about this content improve as they learn to communicate ideas and engage each other in dialogue.

Research has shown the positive effects of collaborative inquiry on the acquisition of scientific ways of knowing and reasoning among language-minority students in middle and high school [4]. This work has also noted that the students' reasoning skills improve as they learn to communicate ideas and engage each other in dialogue [4]. As Brown, Collins and Duguid [5] concluded, this seems to occur best within the context of authentic problems or tasks; tasks that arise in the course of a shared need, concern or problem. In theory, getting students involved in implementing Green Chemistry can provide the context of an authentic problem or task.

3 Differentiating between Green Chemistry and Sustainable Development

As someone who has been an associate editor of four journals that publish what has become known as discipline-based educational research (DBER), the author is unusually sensitive to the importance of the phrase: "For the purpose of this study, we will assume that ...". The idea of explicitly stating assumptions upon which a study will be based is by no means unique to DBER; many fields share a problem that results from having different authors use a particular word or phrase in different ways, with different fundamental assumptions upon which the use of this word or phrase is based. So let me start by noting that some authors seem to conflate the terms *Green Chemistry* and *Sustainable Development* or *Sustainability*. For the purpose of this chapter, the author will assume that these terms should not be used interchangeably. For the sake of argument, the author will use the definition of Green Chemistry proposed by the U.S. Environmental Protection Agency: "... the design of chemical products and processes that reduce or eliminate the generation of hazardous substances" [6].

Having argued that we need to distinguish between Green Chemistry and Sustainable Development, we now need a working definition of the latter term. The International Institute for Sustainable Development [7] has noted that the most frequently quoted definition of this term appeared in the report known as *Our Common Future* from the World Commission on Environment and Development [8]:

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- The concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given.
- The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

We can now understand why the Royal Society of Chemistry (RSC) website suggests that green chemistry "can be considered as chemists aspiring to the principles of Sustainable Development" [9]. And why others have called for "tools to teach and learn about green chemistry, in order to create a sustainable future" [10].

4 Genesis of the Green Chemistry movement

As the author has noted elsewhere [11], the Green Chemistry movement can be traced back to the Pollution Prevention Act of 1990, which represented a fundamental change in national policy. For the first time, the EPA was mandated to focus on preventing pollution at its source rather than treating pollutants once they were formed. Section 6602(b) of the Pollution Prevention Act set forth the following hierarchical policy for the United States [12]:

- Pollution should be prevented or reduced at the source whenever feasible.
- Pollution that cannot be prevented should be recycled in an environmentally safe manner whenever feasible.
- Pollution that cannot be prevented or recycled should be treated in an environmentally safe manner whenever feasible.

– Disposal or other release into the environment should be employed only as a last resort and should be conducted in an environmentally safe manner.

When the Pollution Prevention Act of 1990 was signed into law, Paul Anastas was the head of the Industrial Chemistry Branch at the EPA. In 1991, Anastas invented the term "Green Chemistry" to describe a different way of thinking about how chemistry and chemical engineering are done. Although this is not often recognized, the philosophy behind the Green Chemistry movement was not limited to recognizing potential hazards. As it has been explained on the American Chemical Society (ACS) website [13]:

> It's important to note that the scope of these green chemistry and engineering principles go beyond concerns over hazards from chemical toxicity and include energy conservation, waste reduction, and life cycle considerations such as the use of more sustainable or renewable feedstocks and designing for end of life or the final disposition of the product.

In an interview published in *Nature* in 2011, Anastas was asked: "How did you come up with the name 'Green Chemistry'?" He responded: "… they think I'm joking when I say, well, green is the colour of nature, but in the United States green is also the colour of our money. It's always been about how you meet your environmental and economic goals simultaneously" [14].

A major step forward in the Green Chemistry movement occurred in 1995, when President Clinton created the Presidential Green Chemistry Challenge Awards. These awards did more than give credit where it was due, they served as models for others to follow and a way of tracking progress. For a technology to be considered Green Chemistry, it must be more environmentally benign, more economically viable, and functionally equivalent to or outperform existing alternatives [15]. According to the Warner-Babcock Institute for Green Chemistry website, only 10 % of current technologies are "environmentally benign," while another 25 % "could be made benign relatively easily" [15]. This means there is a great deal of room (65 %) for further innovation.

4.1 12 principles of Green Chemistry

John Warner is recognized as a co-founder of the Green Chemistry movement. Warner worked with Anastas to create the Presidential Green Chemistry Challenge Awards and served as co-author with Anastas of the seminal textbook in the field: *Green Chemistry: Theory and Practice* [16], in which the authors summarized a set of 12 guiding principles. The original wording of these guiding principles can be found on various websites, but the language with which they are described has been made a little less technical in recent years. As described on the EPA website [17] that defines the basics of green chemistry, for example, they are:

1. **Prevent waste**: Design chemical syntheses to prevent waste. Leave no waste to treat or clean up.
2. **Maximize atom economy**: Design syntheses so that the final product contains the maximum proportion of the starting materials. Waste few or no atoms.
3. **Design less hazardous chemical syntheses**: Design syntheses to use and generate substances with little or no toxicity to either humans or the environment.
4. **Design safer chemicals and products**: Design chemical products that are fully effective yet have little or no toxicity.
5. **Use safer solvents and reaction conditions**: Avoid using solvents, separation agents, or other auxiliary chemicals. If you must use these chemicals, use safer ones.
6. **Increase energy efficiency**: Run chemical reactions at room temperature and pressure whenever possible.
7. **Use renewable feedstocks**: Use starting materials (also known as feedstocks) that are renewable rather than depletable. The source of renewable feedstocks is often agricultural products or the wastes of other processes; the source of depletable feedstocks is often fossil fuels (petroleum, natural gas, or coal) or mining operations.
8. **Avoid chemical derivatives**: Avoid using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste.
9. **Use catalysts, not stoichiometric reagents**: Minimize waste by using catalytic reactions. Catalysts are effective in small amounts and can carry out a single reaction many times. They are preferable to stoichiometric reagents, which are used in excess and carry out a reaction only once.

10. **Design chemicals and products to degrade after use**: Design chemical products to break down to innocuous substances after use so that they do not accumulate in the environment.
11. **Analyze in real time to prevent pollution**: Include in-process, real-time monitoring and control during syntheses to minimize or eliminate the formation of byproducts.
12. **Minimize the potential for accidents**: Design chemicals and their physical forms (solid, liquid, or gas) to minimize the potential for chemical accidents including explosions, fires, and releases to the environment.

These principles can be divided into two broad categories: (1) reducing risk and (2) minimizing the environmental footprint. If asked to do so, the author could discuss in great detail the implications of many of these guiding principles in terms of providing new ways to think about the process of both "doing chemistry" and "teaching chemistry." But for now, he would like to emphasize the connection between the social and/or environmental benefits of Green Chemistry as outlined in the 12 principles listed above and the idea of explicitly thinking about our work as chemists within the general context of both "safe practice" and "prudent practice." He would also like to propose an intrinsic connection between the general principles of Green Chemistry and ethical practice that results, in part, because of the intrinsic connection between the basic tenants of chemical health and safety and ethical practice in the chemistry classroom/laboratory.

4.2 12 principles of Green Engineering

Anastas and Zimmerman [18] went on to define green engineering as "the development and commercialization of industrial processes that are economically feasible and reduce the risk to human health and the environment." The guiding principles for green chemical engineering were defined as follows:

1. **Inherent Rather Than Circumstantial**: Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.
2. **Prevention Instead of Treatment**: It is better to prevent waste than to treat or clean up waste after it is formed.
3. **Design for Separation**: Separation and purification operations should be designed to minimize energy consumption and materials use.
4. **Maximize Efficiency**: Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
5. **Output-Pulled Versus Input-Pushed**: Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
6. **Conserve Complexity**: Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7. **Durability Rather Than Immortality**: Targeted durability, not immortality, should be a design goal.
8. **Meet Need, Minimize Excess**: Design for unnecessary capacity or capability (e. g., "one size fits all") solutions should be considered a design flaw.
9. **Minimize Material Diversity**: Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
10. **Integrate Material and Energy Flows**: Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
11. **Design for Commercial "Afterlife"**: Products, processes, and systems should be designed for performance in a commercial "afterlife."
12. **Renewable Rather Than Depleting**: Material and energy inputs should be renewable rather than depleting.

4.3 Implications of the use of the term "design" in the guiding principles

In 2005, the author worked with colleagues from the College of Engineering at Purdue to create what has become the School of Engineering that was built, in part, upon the framework of Chemical Education graduate program at Purdue that had been created roughly 25 years earlier. When he first started working with colleagues in engineering he noticed that they repeatedly tried to differentiate themselves from scientists by claiming: "We do 'design'." His reaction to this argument was to probe their misunderstanding of the nature of science, arguing that "design" was a critical component of the practice of "doing science." Consider the compound whose structure is shown in Figure 1, which was the product of a total synthesis proposed by an organic chemistry graduate student during an oral exam in which the author took part.

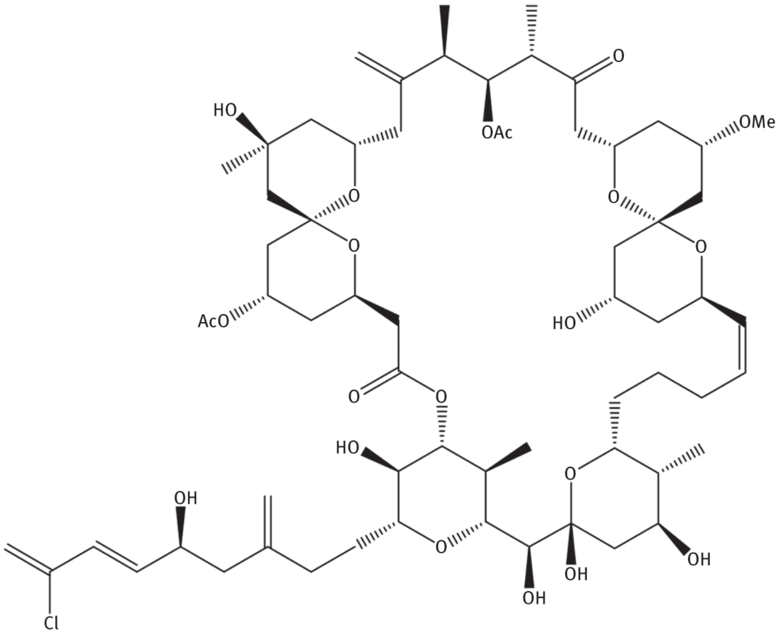

Figure 1: Spongistatin 1: a macrocyclic lactone with broad-spectrum antifungal activity.

If the creation of the multistep process by which one would synthesize this substance is not an exercise in "design," then the author has no understanding of what that word might mean. The other example he used as an illustration of the concept of design in the sciences was to ask his colleagues in engineering to consider the Large Hadron Collider at CERN that was involved in the successful search for the Higgs boson, and asked: Isn't the process whereby literally thousands of physicists were involved in the construction of this apparatus an exercise in "design?" The author's research group went so far as to carry out a study comparing the meaning of the term "design" in such diverse fields as choreography, creative writing, organic chemistry, and engineering [19]. This temporary digression from the flow of discourse in this chapter was inserted as an excuse to remind the reader of the frequency with which the term "design" can be found in the principles of both Green Chemistry and Green Engineering.

5 The ACS Green Chemistry Institute (ACS GCI®)

The Green Chemistry Institute® was created as a not-for-profit corporation in 1997 that became part of the American Chemical Society four years later. The goal of the ACS CGI® is to be "the premier agent of change providing the knowledge, expertise and capabilities to catalyze the movement of the chemical enterprise toward sustainability through the application of green chemistry principles" [20]. Under the heading, "What is Green Chemistry" [21] the ACS website makes a series of important points: "Green chemistry is not politics; it is not a public relation ploy; nor is it a pipe dream. It is a field described as open for innovation, new ideas, and revolutionary progress. Most importantly, it is the future of chemistry."

During one of the annual Green Chemistry and Engineering Conferences, the author was involved in a conversation among a group of industrial chemists who proposed the notion that Green Chemistry is a global effort to solve what are inherently local problems. If this is true, they argued, different geographical regions will have to take different approaches to solving what might appear to be similar problems. Thus, they argued, green chemistry jobs may be unique because they cannot be outsourced. As recently noted in *Chemical and*

Engineering News (C&EN), "The 2011 Pike Research report estimated that the market for chemicals produced through green chemistry approaches will reach nearly $100 billion by 2020, and many industry sectors are vying for their share" [22]

The very existence of this volume is evidence of the commitment of many aspects of what is called "the chemical enterprise" to Green Chemistry. One of the examples the author uses in his own courses is based on the well-known case study involving the synthesis of ibuprofen [23]. He points out the obvious to his students: If you need to make 10 grams of this substance, the traditional idea of "percent yield" is all one needs, and, although one would like to get a better yield, the traditional six-step synthesis of ibuprofen that is characterized by a 40 % yield is "workable." But, once we understand that 30 million pounds of this substance need to be synthesized each year, the production of 45 million pounds of waste is obviously unacceptable. Students therefore readily appreciate the advantage of the three-step synthesis with an atom economy of as much as 99 percent that was developed by the BHC Company, a joint venture of Hoechst Celanese and the Boots Company. They recognize that this process generates more of the desired product, in less time, with less energy, and therefore less impact on the economy. Without having fully integrated the guiding principles of Green Chemistry into their thought process, they can appreciate why the pharmaceutical industry is a particularly good example of the implementation of green chemistry.

Another example from industry that is easily incorporated into introductory classes is the story of sildenafil citrate. Students readily accept the thought that the first priority of a company might be getting a product "out the door." And they readily understand that, once this has happened, the next priority might be improving the efficiency. As noted by Poliakoff [24], the original synthesis of the active ingredient in the "blue pill" sold by Pfizer once consumed 1350 liters of solvent per liter of product. Today, it consumes only 6 liters of solvent per kilogram of product. So they are willing to accept the concept of the "triple bottom line;" the idea that Green Chemistry can have strong economic benefits as well as both social and environmental benefits.

Having set the basis for thinking about Green Chemistry in industry and the reasons why many companies are willing to pay the cost of joining the Pharmaceutical or Industrial Roundtables organized by the ACS GCI™, the author has been able to bring into the discussion more subtle examples, such as the use of 2-methyltetrahydrofuran. He starts by noting that companies often have a "Green Chemistry" component on their website. He then points out that the first example of Green Chemistry on the Aldrich Chemical website [25] was a substance he first learned about by talking to industrial chemists at one of the Green Chemistry and Engineering conference: 2-methyltetrahydrofuran (Figure 2).

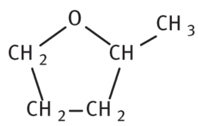

Figure 2: The structure of 2-methyltetrahydrofuran.

Having distinguished between the structures of this compound and THF, he asks the question: What makes this solvent "green"? It is obtained from renewable resources such as corncobs or the fibrous material that remains after sugarcane or sorghum stalks are crushed. It is also safer than THF because it is less likely to form peroxides. It is both a polar solvent and an aprotic solvent, so Grignard reagents are more soluble in 2-MeTHF than THF. Because it has only a limited solubility in water, 2-MeTHF is much easier to separate and recover, thereby reducing the waste stream. Finally, it has a low heat of vaporization, which means that less energy is consumed during distillation and recovery.

6 Green Chemistry in the classroom

Regardless of whether one is an industrial chemist worrying about how to make several million pounds of a substance or an instructor thinking about new ways of overcoming the difficulties associated with the teaching and learning of chemistry, Green Chemistry does not change the facts or principles of chemistry. It just asks us to bring a new dimension into our thought process; a dimension in which:

- Chemistry is actively integrated into the world around us.
- A priority is placed on minimizing potentially negative effects on the environment.
- Where both practicing chemists and students taking chemistry for the first (and perhaps last) time are actively involved in thinking about safe practice,

– Where minimizing waste and maximizing atom-economy become more important concepts than the traditional driving factor of "percent yield."

– Where the notion of limited resources is understood and resources that are used are renewable.

The Green Chemistry movement reminds us of something we ask students to do that is often not done by practicing chemists: Writing a balanced equation so that attention is focused on not just the starting materials and target of the reaction, but the waste generated in the course of the reaction.

The author believes that examples of green chemistry should be incorporated into every chemistry course, at any level; from the introduction to chemistry taught in the K-12 classroom through the last course graduate students take to earn a Ph.D. in chemistry or chemical engineering. A clear understanding of the philosophy upon which the Green Chemistry movement is based is essential for the handful of students from the general population who will go on to pursue careers in the chemical enterprise. But it is also useful for the vast majority of students who will pursue careers in other fields because it can provide a basis for connecting the concepts and facts we ask them to learn to concrete examples that are likely to be more "relevant" than the traditional exercises that have dominated our courses for so many years.

6.1 Beyond benign

At about the same time that proponents were first formalizing what became the Green Chemistry movement, a book was published called *Way Past Cool* [26]. The idea upon which it was based is that it is easy to be "cool," but much more difficult to be "way past cool." Within this context, let's turn to the work of an organization known as "Beyond Benign." (Not just "benign," but "beyond benign.") As noted on their website [27], the mission of Beyond Benign is to provide "… scientists, educators and citizens with the tools to teach and learn about green chemistry, in order to create a sustainable future," and its vision is "to revolutionize the way chemistry is taught to better prepare students to engage with their world while connecting chemistry, human health and the environment" [10]. Beyond Benign was created by John Warner to provide an approach for scientists involved in Green Chemistry to reach out to the public because of his belief that:

> Green Chemistry provides the perfect platform for communicating the importance of science in providing solutions for many of society's challenges because Green Chemistry inherently minimizes the impacts of science on the environment and it is a sustainable approach to chemistry. The relationship between Green Chemistry and the environment provides a uniquely positive, solutions-based starting point for encouraging younger students, who are greatly interested in the environment, to consider positive contributions they can make in any scientific field [26].

Historically, Beyond Benign focused on three aspects of the Green Chemistry movement: (1) the K-12 curriculum, (2) community outreach, and (3) workforce development. The K-12 efforts are based on the idea that the concepts of Green Chemistry and Sustainability will be essential knowledge for all future scientists and educated citizens. Beyond Benign therefore produces lesson plans, curriculum materials, and training programs for the K-12 community.

The website for Beyond Benign has sections devoted to colleges and universities, a Fellows program, and both online courses for educators and online workshops. It provides links to Green Chemistry resources on the web; publications; consumer guides; a "how to" guide to incorporating Green Chemistry concepts and activities into a year-long chemistry course; lessons "for teachers, by teachers" for use in middle-school or high-school classrooms; information about a Green Math, Engineering and Technology project; introductions to biotechnology for use by either middle-school or high-school teachers; access to a peer reviewed journal *Green Chemistry Letters & Reviews*; materials "by professors, for professors" targeted toward community colleges; and information about workforce development proposing the use of Green Chemistry as a tool for regional economic development and job creation.

In different contexts, and using slightly different language, the co-founders of the Green Chemistry movement – Paul Anastas and John Warner – have each proposed a metric upon which to judge the success of the Green Chemistry movement: It will be successful, they argue, when the term Green Chemistry disappears because it will have become integrated into the practice of either "doing chemistry" or "teaching chemistry.

No-one would argue, however, that we are close to having achieved that goal. As a step in the right direction, a program known as the *Green Chemistry Commitmen*t [28] has been created to bring together a Community of Practice that would be built around the shared goals of: (1) expanding the number of practitioners of green chemistry, (2) increasing departmental/institutional resources devoted to green chemistry, (3) improving connections between academics and industry, and (4) bringing about systemic and lasting changes in the way chemistry is taught.

6.2 The Green Chemistry commitment

The goals of the faculty involved in the *Green Chemistry Commitment* include uniting the academic community around a shared set of student learning objectives, providing a way to track progress of the community, and providing direction for outreach and advocacy. That is the reason why the author has chosen to incorporate the term "Community of Practice" into the description of the *Green Chemistry Commitment*

The section of the *Green Chemistry Commitment* document devoted to departments or institutions states that the department that commits itself to signing this document believes that *all* chemistry majors should be proficient in the following green chemistry competencies upon graduation:

Theory: Have a working knowledge of the twelve principles of green chemistry.

Toxicology: Have an understanding of the principles of toxicology, the molecular mechanisms of how chemicals affect human health and the environment, and the resources to identify and assess molecular hazards.

Laboratory Skills: Possess the ability to assess chemical products and processes and design greener alternatives when appropriate.

Application: Be prepared to serve society in their professional capacity as scientists and professionals through the articulation, evaluation, and employment of methods and chemicals that are benign for human health and the environment.

The document that indicates that a department is going to adopt the *Green Chemistry Commitment* requires the signature of both the chair of the chemistry department and at least one administrator at the level of dean, provost, or university president to confirm the notion that this is, in fact, a long-term commitment by the department to these goals.

The student learning objectives/competency related to toxicology in the *Green Chemistry Commitment* deserves special attention. Proponents of this competency should appreciate a point Anastas made in the interview published in *Nature*

> When I was getting my PhD in chemistry I was expected to translate technical articles from French and German to English ... But I can tell you I have never, ever, had to translate an article ... in all of my working life. And yet there was never any requirement that I needed to know the first thing about toxicity or the hazards of the tools of my trade – the chemicals. I never had to take a test that required me to understand the consequences of the molecules that I was introducing into the Universe or the ones that I was using on a daily basis. There's an absurdity there that needs to be addressed [14]

While discussing the Green Chemistry Commitment with faculty at various institutions, the author has noted that the challenge many of these individuals believe they face is finding resources to introduce toxicology. The author has found that using the text on *Laboratory Safety for Chemistry Students* [29] as part of an introduction to safety in a sophomore seminar course provides a basis for introducing some of the basic ideas of toxicology into the chemistry major curriculum. A conversation with executives at Chemical Abstracts Service about the use of SciFinder as a resource in this area suggested that information about toxicology might be available in this resource for perhaps 250,000 of the more than 100 million compounds in the database. It might also be noted that there is an ACS online short course entitled *Toxicology for Chemists* [30], a text entitled *Fundamental Toxicology For Chemists* published by the RSC [31], a toxicology data network (TOXNET), and handbooks on toxicology [32, 33]

7 The "triple bottom line" in academics

When examples of Green Chemistry are threaded into the fabric of the course, it doesn't take much time to convince students of the legitimacy of the "triple bottom line" within the context of practicing chemists working in industry. The author's experience has shown that they soon recognize that there are economic, social and environmental benefits when *someone else* adopts this mode of thinking. But that does not mean that they also appreciate that similar benefits can be achieved within their own activities as students.

One way of getting them to think about the implications of the Green Chemistry movement on academics is to give them examples from the article entitled "It's even cheaper being green," which appeared in the *Chemistry World* magazine distributed to RSC members [34]. That article showed how the investment of funds in the short term can have long-term returns in the form of recurring lower costs for the department. Andrea Sella, from University College London is quoted, for example, as noting: "... because energy is essentially invisible, most of us have little or no idea even of the order of magnitude of what we're using." The vice-chancellor at Cambridge, himself a chemist, was quoted as noting that chemistry labs are often found in older buildings that have been remodeled, "... so you end up with a complicated building that nobody really fully understands," adding:

"Facilities managers have a complex job just trying to keep water flowing through the pipes and nowhere else, and the electricity in the wires and nowhere else." The *Chemistry World* article noted the existence of a not-for-profit organization – S-Lab – whose director was quoted as saying: "'Three to four years ago, most people didn't imagine that you could do things differently in chemistry labs … They thought it was all a given; that the designs of the ventilation systems, which account for the majority of lab energy use, were fixed; the way you operate is the way it's always been done and that's the way it will always be done. But people are beginning to wake up to the fact that there are alternatives."

In the same year that the Pollution Prevention Act was enacted by Congress, a volume entitled *Assessment in the Service of Instruction* [35] was published. In the preface, Shirley Malcom argued: that "… assessment should at least:

- be free of bias,
- reflect what is being taught and give us information to improve instruction for a class or to diagnose problems or to identify misconceptions of an individual,
- allow us to measure the effectiveness of a teacher or a curriculum,
- reflect what *should* be taught or at least what should be valued."

In the same volume, Lovitts and Champagne [36] stated what might be considered an "eternal verity" – something that will be true until the end of time – when they noted that: "It is generally conceded that what does not get assessed does not get taught."

If the Green Chemistry movement is something to be valued, it must also be incorporated into student assessment. But, it should be remembered that the idea that something should be assessed does not mean it has to appear on exams; it can also be incorporated into the assessment of lab activities associated with the course. A variety of questions can be envisioned, including: Given the difference between the properties of THF and 2-methylTHF, list five reasons why the use of 2-methylTHF would be consistent with a Green Chemistry philosophy? What aspects of the lab done this week do you believe were changed by your instructor when they tried to bring the Green Chemistry thought process into this experiment? In what ways might this week's experiment be improved by introducing changes that represent the philosophy of the Green Chemistry movement? In what ways could this week's experiment be made safer?

If one believes that assessment is best associated with exams, there are a lot of relatively simple open-ended questions available to you. Where is the idea of the "triple bottom line" exhibited in the following guiding principles: *Design less hazardous chemical syntheses, design safer chemicals and products*, and *use safer solvents and reaction conditions?* Or, in what ways is the guiding principle advocating chemists to *design chemicals and products to degrade after use* consistent with the efforts at your institution to implement a campus-wide commitment to the green environmental movement? Or, in what ways are the examples of Green Chemistry you've experienced in this course examples of efforts toward the goal of sustainable development?

As an example of the effect the guiding principles of Green Chemistry has had on the author's life in academics, think about the factors that needed to be considered when he first joined the faculty at Purdue, 40 years ago. At that time, Purdue had more than 5000 students taking General Chemistry each fall semester. Imagine the aspects of size and scale he faced when trying to introduce new experiments into just one of the courses in this program, which enrolled roughly 2500 students. Any experiment added to the curriculum had to be compatible with the equipment available in each of the thousands of laboratory drawers. The cost of purchasing chemicals was an important constraint because literally thousands of students were doing the same experiment each week. Safety, of course, was another important factor influencing the design of new experiments.

Now, try to imagine the constraining forces he would face if he was trying to do the same thing today. It should be easy to appreciate that the cost of disposal of waste products generated in any experiment introduced into the curriculum may have become a more important factor than the cost of purchasing the chemicals in the first place.

8 Reflections on the evolution of Green Chemistry in academics

Ten years ago, The National Research Council [37] published a report entitled *Exploring Opportunities in Green Chemistry and Engineering Education* that was based on a two-day workshop organized by the Chemical Sciences Roundtable. Participants at this workshop correctly noted the existence of "green islands" corresponding to "relatively small pockets of activity in green chemistry education." But they also correctly noted that "… sustainability is the single most important challenge for our civilization for at least the next 100 years."

Recently, the ACS GCI® completed a review of the status of green chemistry education in the United States [38]. The author of this chapter concluded from reading this report that additional "green islands" are gradually appearing and, for the first time, these islands include a representative sample of research-intensive institutions. Consider, for example, institutions that are members of the Association of American Universities (AAU), which includes universities "... on the leading edge of innovation, scholarship, and solutions that contribute to the nation's economy, security, and well-being." This group of 60 research-intensive institutions "... award nearly one-half of all U.S. doctoral degrees and 55 percent of those in the sciences and engineering" [39]. At the time this chapter was written, 25 % of the members of the AAU had a green chemistry academic program, including: Berkeley, Cal Tech, Carnegie Mellon, Florida, Georgia Tech, Indiana, Iowa State, Michigan State, Michigan, Ohio State, Oregon, Pittsburgh, Stony Brook (SUNY), Washington, and Yale.

The ACS GCI® report noted the widespread commitment at the institutional level among colleges and universities to the philosophy of the green environment movement. What the author finds frustrating is that this campus-wide program often exists without any involvement of the Chemistry Department.

This report also noted that, in spite of the dissemination of resources available to help instructors introduce green chemistry into their courses, most of the green chemistry courses being offered are introductory courses rather than upper-level courses designed to meet the needs of students enrolled in STEM majors. The ACS GCI® report also noted that the majority of NSF funds (79 %) devoted to research on green chemistry and engineering were given to large, research-intensive institutions, and yet it was the smaller schools who were more likely to publically promote green chemistry initiatives.

In discussions with colleagues in chemical education from a wide variety of institutions and with staff at the ACS GCI®, the author has reached several conclusions.

– When Green Chemistry is introduced it is usually the result of a "bottom-up" rather than "top-down" implementation; it is virtually always introduced because of the beliefs or values of one or more faculty at the bottom of the organization chart, rather than because it was mandated by a department head or dean who occupies the top of chart.
– When Green Chemistry is introduced it is done so passionately, by instructors whose commitment to the principles of Green Chemistry and Sustainability are absolutely remarkable.
– Green Chemistry is often endorsed with equal passion by undergraduate chemistry majors who work with these instructors.
– Green Chemistry is most often introduced in a way that is the most convenient; by incorporating it into existing courses, rather than by creating a separate course, although separate, upper-level courses on green chemistry do exist.
– Separate, upper-level Green Chemistry courses are unusually "fragile" or "volatile." The author is familiar with a number of instances where an upper-level course was created, but soon vanished because well-intentioned instructors who created the Green Chemistry course were pulled out of these courses to staff more traditional courses.
– Although there are examples of institutions where a Green Chemistry commitment has been integrated throughout the undergraduate curriculum, they are still rare, and they are most likely to occur in relatively small departments where it is significantly easier to reach the consensus necessary to do this.

The author has also noted that the twenty-first century is following a pattern that characterized curriculum development/reform projects throughout the second-half of the previous century. The first characteristic of this pattern, which has appeared over and over again for at least 60 years, can be appreciated by noting that far more time, effort, and resources go into the development of curriculum materials than into dissemination of these materials, with the notable exception of the Green Chemistry group at the University of Oregon who have done an extraordinary job in getting materials distributed among people who would be likely to use them [40].

The second characteristic of curriculum development/reform projects can be seen by noting that, however small the amount of time, effort and resources devoted to dissemination of the curriculum materials, it is still an order of magnitude (or more!) larger than the time, effort and resources devoted to the evaluation of the effect of the new curriculum materials on students or their instructors. Periodically, one encounters papers whose authors are honest enough to note that no formal, large-scale evaluation program was carried out because all of the funding was tied to the development and dissemination of the curriculum materials [41].

9 Why there might be a "quadruple bottom line" in academics

The title of this chapter was taken from a paper presented by the author in a symposium at the 2016 Biennial Conference on Chemical Education. It builds on the idea of the triple bottom line that was one of the take-home messages from the author's interactions with members of both the Pharmaceutical Roundtable and the Chemical Manufacturers Roundtable at the first ACS GCI® conference he attended. He has found that undergraduates readily accept the idea that Green Chemistry can have strong, positive effects within the domains of economic, social and environmental benefits. But these factors, alone, cannot explain why so many students respond so enthusiastically to the Green Chemistry movement when the examples cited by their instructors seldom, if ever, seem to have a direct impact on what happens in the students' daily lives. To explain that effect, we need to digress to understand the fourth element in the quadruple bottom line: *relevance*.

At first glance, most readers of this chapter will assume that the term *relevance* needs no further explanation. If they happen to look at the definition of *relevance* on the Merriam-Webster website they might even note the apparent validity of the example used there: "giving *relevance* to college courses." But please forgive the author as he asks for a moment to expand on the history of the call for "relevance" in our courses and then describes a recently proposed model that clarifies some of the inconsistencies in the way the term is used when referring to the chemistry classroom.

The chapter entitled "Understanding the change toward a greener chemistry by those who do chemistry and those who teach chemistry" [11] to which the author has periodically referred was written for his colleagues in "science education." It is an example of something he has done repeatedly throughout his career – writing about chemistry for those doing educational research or writing about the results of research in education for chemists. The chapter appeared in a book [42] that built on a paper that probed the question: What does it mean to ask teachers to make their course "more relevant" to students? [43].

10 A new way of looking at "relevance"

It has been 45 years since Gallagher [44] proposed the creation of "STS" courses that would show how science is relevant to everyday life by integrating science, technology and society. By 1982, the National Association of Science Teachers began a report on STS courses by noting: "The goal of science education during the 1980s is to develop scientifically literate individuals who understand how science, technology and society influence one another and who are able to make use of this knowledge in their everyday decision making. This individual both appreciates the value of science and technology in society and understands their limitations" [45].

With support from NSF, the ACS took a step toward an STS course by developing a "context-based" high-school chemistry course known as *Chemistry in the Community* intended to "provoke student interest and involvement in chemistry … by embedding chemistry within society, where chemistry daily impacts human lives, rather than metaphorically confining chemistry to laboratory flasks … and brown bottles" [46]. In other words, to make the high-school course more *relevant*. The success of *Chem Comm* led the Society to create a one-semester, college-level text for non-science majors known as *Chemistry in Context* [47]. More or less the same factors led to the creation of "context-based" chemistry courses in other countries at more or less the same time [41, 48, 49].

To illustrate the problem with the idea of making chemistry courses *more relevant*, let's return to the period when so much activity surrounding the development of "context-based" chemistry courses occurred and note that Newton [50] began a paper on "relevance and science education" by noting: "… science teachers are increasingly exhorted to make their teaching relevant but, in general, the notion of relevance in science education seems fraught with inconsistency, obscurity and ambiguity." Newton noted that the term *relevance* is sometimes used within a context that allows students to relate science to their daily lives; at times it seems to imply connecting the course content to their prior experience or existing ideas students bring to the course; whereas at still other times it seems to imply that the material being taught should be related to the world they will experience as adults. Newton concluded the introductory section of his paper as follows: "The notion of relevance is not a simple one. It seems at the least unhelpful and at worst counterproductive to urge a teacher to be relevant in terms which are abstract and diffuse. It might be useful if some aspects of the notion of relevance were to be clarified." Perhaps it should not be surprising that debates about *relevance* in science education have been going on for more than 40 years [51].

Recently, a model developed by Stucky et al.,has been proposed that might help us understand that there are three dimensions within which *relevance* can be viewed [43]. Each of these dimensions can be viewed as a plane defined by the same pair of axes. One axis reflects the continuum between two points in time, now and the future. The other can be viewed in terms of a perspective that builds on *Self-Determination Theory* [52, 53], which distinguishes between different types of motivation by noting: "The most basic distinction is between intrinsic motivation, which refers to doing something because it is inherently interesting or enjoyable, and extrinsic motivation, which refers to doing something because it leads to a separable outcome" [53].

The first dimension of relevance can be viewed as the *individual dimension*. Chemistry, in general, or Green Chemistry, in specific, can be thought of in terms of a student's innate interest or curiosity in one corner of a plane corresponding to both the "present" and an "intrinsic" motivation. Another corner, corresponding to the "present" and "extrinsic" motivation might be thought of in terms of the student's goal of getting a good grade. As one moves toward the corner defined by "future" and "intrinsic," one might find the idea of material that might be associated with an individual's developing skills to help them succeed in life. And the combination of "future" and "extrinsic" might be associated with acting responsibly as individuals in their future lives.

The *societal dimension* of relevance can be viewed using the same axes; present versus future and intrinsic versus extrinsic. The corner associated with the present and an intrinsic point of view might be thought of in terms of the students' efforts to find their own place in society, whereas future and intrinsic could be viewed as promoting one's own interests in the societal discourse they will encounter. The present and extrinsic corner might be associated with learning how to behave in society, whereas the future and extrinsic corner might be seen as behaving as a responsible, adult citizen within the context of society, as a whole.

The *vocational dimension* can be seen as a continuum along the set of points characterized by an intrinsic motivation as one views the present emphasis on developing the skill set that orients the student toward potential careers moving toward the goal of obtaining a job one can value. Moving along the extrinsic side of the diagram one can envision a present focus on doing well enough to qualify for subsequent courses at this point in time toward the important future goal of contributing to society's economic growth.

The author has found the model developed by Stuckey et al. [43] useful as he thinks about how to bring the final element of the quadruple bottom line into his classroom, regardless of which chemistry course he is teaching that semester. Hopefully, others will find it useful as well because all three dimensions of *relevance* are important as instructors who are passionate about the role that Green Chemistry can play interact with students – regardless of their major – who enroll in our courses as a step toward both their future careers and their participation as a scientifically literate citizen.

References

[1] Wenger E. Communities of practice: learning, meaning, and identity. Cambridge, UK: Cambridge University Press, 1988.
[2] Macklin AS. Theoretical frameworks for research in chemistry/science education. In: Bodner GM and Orgill M, editors. Communities of Practice Upper Saddle River, NJ: Prentice Hall, 2007:195–217.
[3] Surowiecki J. The wisdom of crowds: why the many are smarter than the few and how collective wisdom shapes business, economies, societies and nations. New York, NY: Doubleday, 2004.
[4] Rosebery AS, Warren B, Conant FR. Appropriating scientific discourse: findings from language minority classrooms. J Learn Sci. 1992;2:61–94.
[5] Brown JS, Collins A, Duguid P. Situated cognition and the culture of learning. Educ Res. 1989;18:32–42.
[6] Green Chemistry. Aug 2014 Available at: http://www2.epa.gov/green-chemistry/. Accessed27Aug2014.
[7] International Institute for Sustainable Development. Aug 2014 Available at: http://www.iisd.org/sd/. Accessed27Aug2014.
[8] World Commission on Environment and Development (WCED). Our common future. Oxford, UK: Oxford University Press, 1987:43.
[9] Green Chemistry. Aug 2014 Available at: http://www.rsc.org/ScienceAndTechnology/Policy/EHSC/EHSCnotesonGreenChemistry.asp/. Accessed27Aug2014.
[10] Beyond Benign: Green Chemistry Education. Aug 2014 Available at: http://www.beyondbenign.org/. Accessed27Aug2014.
[11] Bodner GM. Understanding the change toward a greener chemistry by those who do chemistry and those who teach chemistry. In: Eilks I, Hofstein A, editors. Relevant chemistry education – from theory to practice. Rotterdam: Sense Publishers, 2015:263–284.
[12] Pollution Prevention: Definitions. Aug 2014 Available at: http://www.epa.gov/p2/pubs/p2policy/definitions.htm/. Accessed27Aug2014.
[13] Green Chemistry Definition. Aug 2014 Available at: https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/definition.html/. Accessed27Aug2014.
[14] Q&A: Paul Anastas. Aug 2014 Available at: http://www.nature.com/news/2011/110105/full/469018a/box/2.html/. Accessed27Aug2014.
[15] About Green Chemistry. Aug 2014 Available at: http://www.warnerbabcock.com/green_chemistry/about_green_chemistry.asp/. Accessed27Aug2014.
[16] Anastas PA, Warner JC. Green chemistry: theory and practice. Oxford, UK: Oxford University Press, 2000.
[17] Basics of Green Chemistry. Aug 2014 Available at: https://www.epa.gov/greenchemistry/basics-green-chemistry#twelv/. Accessed27Aug2014.
[18] Anastas PT, Zimmerman JB. Design through the 12 principles of green engineering. Environ Sci Tech. 2003;37 94A-101A.
[19] Daly S, Adams R, Bodner GM. What does it mean to design? A qualitative investigation of design professionals' experiences. J Eng Educ. 2012;101(2):187–219.
[20] History of the Green Chemistry Institute. Aug 2014 Available at: http://www.acs.org/content/acs/en/greenchemistry/about/history.html/. Accessed27Aug2014.

[21] What is Green Chemistry?. Aug 2014 Available at: https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry.html/. Accessed27Aug2014.
[22] Vorhees K, Hutchison JE. Green Chemistry Education Roadmap charts the path ahead. Chem Eng News. 2015;93(38):46.
[23] Synthesis of ibuprofen. Aug 2014 Available at: http://www.epa.ohio.gov/portals/41/p2/ibuprofencasestudy.pdf/. Accessed: 27Aug2014.
[24] Sildenafil Citrate: Green Chemistry. Aug 2014 Available at: http://www.tes.co.uk/teaching-resource/Sildenafil-Citrate-Green-Chemistry-6397172/. Accessed27Aug2014.
[25] Greener Alternatives. Aug 2014 Available at: http://www.sigmaaldrich.com/chemistry/greener-alternatives.html/. Accessed27Aug2014.
[26] Mowry J. Way past cool. New York, NY: Farrar Straus Giroux, 1992.
[27] Beyond Benign: Green Chemistry Education. Aug 2014 Available at: http://www.beyondbenign.us/home/about/about.html. Accessed27Aug2014.
[28] Green Chemistry Commitment. Aug 2014 Available at: http://www.greenchemistrycommitment.org/. Accessed27Aug2014.
[29] Hill RH, Finster D. Laboratory safety for chemistry students, 2nd ed New York: John Wiley & Sons, 2016.
[30] ACS. Toxicology for chemists online short course. Aug 2014 no date. Available at: http://proed.acs.org/course-catalog/courses/toxicology-for-chemists-online-short-course/. Accessed27Aug2014.
[31] Duffus JH, Worth HG. Fundamental toxicology for chemists. Cambridge, UK: Royal Society of Chemistry, 1996.
[32] Derelanko MJ, Auletta CS. Handbook of toxicology, 3rd ed Boca Raton, Fl: CRC Press, 2014.
[33] Murray L, Little M, Pascu O, Hoggett K. Toxicology handbook, 3rd ed Australia: Elsevier, 2015.
[34] Broadwirth P. It's even cheaper being green. Chem World-UK. 2014 May;2014:50–53.
[35] Champagne AB, Lovitts BE, Calinger B. Assessment in the service of instruction: papers from the 1990 AAAS forum for school science. Washington, DC: American Association for the Advancement of Science, 1990.
[36] Lovitts BE, Champagne AB, Champagne AB, Lovitts BE, Calinger B. Assessment in the service of instruction: papers from the 1990 AAAS forum for school science. Washington, DC: American Association for the Advancement of Science, 1990:1–13.
[37] National Research Council. Exploring opportunities in green chemistry and engineering education: a workshop summary to the chemical sciences roundtable. Washington, DC: The National Academies Press, 2007.
[38] Constable D. Personal communication 2014.
[39] Association of American Universities. August 2014 Available at: https://www.aau.edu/. Accessed27August2014.
[40] University of Oregon Green Chemistry Program. Aug 2014 Available at: http://greenchem.uoregon.edu/. Accessed27Aug2014.
[41] Bennett J, Lubben F. Context-based chemistry: the Salters approach. Intern J Sci Educ. 2006;28:999–1015.
[42] Eilks I, Hofstein A. Relevant chemistry education – from theory to practice. Rotterdam: Sense Publishers, 2015.
[43] Stuckey M, Hofstein A, Mamlock-Naaman R, Eilks I. The meaning of 'relevance'in science education and its implications for the science curriculum. Stud Sci Educ. 2013;49:1–34.
[44] Gallagher JJ. A broader base for science teaching. Sci Educ. 1971;55(3):329–338.
[45] National Science Teachers Association. Science-technology-society: science education for the 1980's. Washington, DC: National Science Teachers Association, 1982.
[46] Heikkinen HW. To form a favorable idea of chemistry 1. J Chem Educ. 2010;87:680–684.
[47] Schwartz AT, Bunce DM, Silberman RG, Stanitski CL, Stration WJ, Zipp AP. 'Chemistry in Context": weaving the web. J Chem Educ. 1994;71:1041–1044.
[48] Hofstein A, Kesner M. Industrial chemistry and school chemistry: making chemistry studies more relevant. Intern J Sci Educ. 2006;28:1017–1039.
[49] Parchmann I, Gräsel C, Baer A, Nentwig P, Demuth R, Ralle B. "Chemie im Kontext": A symbiotic implementation of a context-based teaching and learning approach. Intern J Sci Educ. 2006;28:1041–1062.
[50] Newton DP. Relevance and science education. Educ Phil Theor. 1988;20(2):7–12.
[51] Fensham PJ. Increasing the relevance of science and technology education for all students in the 21st century. Sci Educ Intern. 2004;15:7–26.
[52] Deci EL, Ryan RM. Intrinsic motivation and self-determination in human behavior. New York: Plenum, 1985.
[53] Ryan RM, Deci EL. Intrinsic and extrinsic motivations: classic definitions and new directions. Contemp Educ Psychol. 2000;25:54–67.

Arthur E. Kelly Distinguished Professor of Chemistry, Education and Engineering.