Green Chemistry

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Infusing the Chemistry Curriculum with Green Chemistry Using Real-World Examples, Web Modules, and Atom Economy in Organic Chemistry Courses

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This article describes the efforts of the faculty at the University of Scranton to infuse green chemistry into the chemistry curriculum and illustrates the use of Web-based modules and green chemistry concepts in the two-semester organic sequence. Future papers will describe our modules, activities, and experiences in the areas of general and inorganic chemistry, biochemistry and chemical toxicology, environmental and polymer chemistry, and advanced organic and industrial chemistry courses.

When producing a new chemical, chemists have too often ignored the environmental effects of both the chemical and the process by which it is made. With awareness of chemical contamination deepening, chemists must consider these environmental effects as one of the prime factors in deciding whether or not to produce a chemical and in deciding the process by which it will be prepared. Chemists must begin to view all chemistry in light of its potential damage to the environment. Green chemistry has evolved out of this growing awareness. The principles of green chemistry trace back to the U.S. Pollution Prevention Act of 1990; green chemistry became a formal focus of the U.S. Environmental Protection Agency (EPA) in 1991. Green chemistry aims to eliminate or reduce the use or production of hazardous substances. Green chemistry focuses on:

- Minimizing hazardous and non-hazardous waste.
- Minimizing energy requirements.
- Minimizing resource use while utilizing renewable resources whenever possible.

Bringing Green Chemistry into the Classroom

An Upper-Level Course in Green Chemistry

One way to teach green chemistry is to develop an upper level course in green chemistry taken by those students who have a substantial background in general, organic, and perhaps inorganic and physical chemistry. This approach has been taken by Matlack *(1)* among others. Faculty members such as Terry Collins, Jim Hutchison, and David Brown teach stand-alone green chemistry courses. This avenue offers the advantage of being able to concentrate only on green chemistry, and to teach and discuss green chemistry at a very technical level owing to the student's chemistry background. These students may be the ones who actually become the practitioners of green chemistry. The disadvantage of this approach is that many universities may not be able to offer such a course for a number of reasons, including a lack of available or qualified personnel and an already overcrowded curriculum. Also, an elective green chemistry course would be taken by relatively few students (upper-class undergraduates and graduate students) because of the considerable number of prerequisites. Even more importantly, a course dedicated to green chemistry may also give the false impression that green chemistry is a field unto itself rather than an ideal that must be applied to all areas of chemistry.

Infusing Existing Courses with Green Chemistry

The approach that we have taken is to infuse courses across the undergraduate chemistry curriculum with green chemistry. The importance and concepts of green chemistry are introduced into the first-year general chemistry course, expanded and reinforced in the second-year organic chemistry course, and so on throughout most of the courses in the chemistry curriculum. This approach has several advantages:

- More students are exposed to green chemistry, including majors and non-majors. Even though many of these students will not likely become chemists, many will become professionals who may make scientific, ethical, policy, or business decisions regarding green chemistry or other sustainable practices. This will also help to improve the image of chemistry among a much larger group of individuals.
- The students are continually exposed to green chemistry throughout the curriculum and are forced to consider its application in all areas of chemistry realizing that green chemistry permeates all chemical disciplines and is not a field unto itself.
- No new course needs to be developed and inserted into an already crowded curriculum.
- Green chemistry may be introduced by "greening" a topic that is already discussed in a particular course. This allows for the introduction of green chemistry into a course while adding little new material to an already congested course.

Posters and Oral Presentations

Our original attempt to bring green chemistry into the chemistry curriculum was in 1996, which coincided with the first U.S. Presidential Green Chemistry Challenge (PGCC) awards *(2).* The PGCC awards are given annually and provide a means for recognizing those who have made outstanding achievements in green chemistry. Our efforts focused on using the PGCC awards to introduce green chemistry into our environmental chemistry course. In this course students are required to select one of the award-winning PGCC proposals and present an oral and poster presentation on the topic of the proposal. In preparing their presentations, students must contact the authors of the proposal, search the literature using STN, and search the Web. An article in this *Journal (3)* and the course syllabus *(4)* provide additional information about this project.

The environmental chemistry course at the University of Scranton is a third year course required for environmental science majors and has prerequisites of two semesters of general and organic chemistry. Although this course can be taken as an elective by our chemistry and biochemistry majors it generally has an enrollment of 10–12 students. Thus very few students are exposed to green chemistry through this course and it was necessary to broaden our efforts in order to expose additional students to green chemistry.

Developing Green Chemistry Educational Materials

Writing Real-World Cases in Green Chemistry

In 1998 the EPA and the ACS partnered to form the Green Chemistry Educational Materials Development Project *(5).* Both of these agencies recognized the need to include green chemistry in the educational process. The initial focus of this project was to develop:

- An annotated bibliography of green chemistry
- Real-world case material on green chemistry
- Green laboratory modules
- Short courses in green chemistry

Our involvement in the project dealt with the cases and resulted in the book *Real-World Cases in Green Chemistry (6).* The PGCC award proposals have provided the basic materials on which the real-world cases were developed. These cases are cast in a manner that permits their use in a variety of ways in the undergraduate classroom. Green chemistry crosses many of the disciplines of chemistry and thus green chemistry is easily infused into most of the mainstream courses found in a typical undergraduate curriculum.

Each case in *Real-World Cases in Green Chemistry* consists of several sections including the overview, which provides a simple summary of the environmental problem associated with a particular product or process and the solution to this environmental problem that green chemistry provides. The summary allows one to quickly ascertain the relevance of the material to a particular course. The background section provides material that is necessary to understand the case, and a more detailed look at the chemistry currently used and its associated environmental problems. The green chemistry section presents information about the more environmentally benign chemistry that was developed and how this product or process diminishes the negative environmental impact of the traditional protocol. The green chemistry in action section discusses the actual application of the green chemistry. Each one also includes a Notes to Instructors section that suggests ways to use the modules, including which courses they may apply to. The cases are effective for infusing courses from general chemistry to upper level courses, including graduate courses, with green chemistry. Those who teach a course in green chemistry may also find this work useful.

Adapting Cases for Web-Based Teaching Modules

Our next task was to take the material in the cases and to develop green chemistry teaching modules demonstrating how these cases could be used to infuse green chemistry into specific courses. The intention was to take the basic, general information provided by a case and amend and supplement it so that it would apply to a specific topic in a particular course. The topic would simply be “greened”. This would allow for inclusion of green chemistry into a course, without adding more material to an already overcrowded course.

We began this project in the summer of 2000 with the aid of a grant from the Dreyfus Foundation Special Grant Program in the Chemical Sciences *(7)* and with additional funds provided by the ACS, EPA, and the University of Scranton. Six faculty members[1] from Scranton contributed to this project, producing nine green chemistry teaching modules and an introduction to green chemistry. Starting in the fall of 2000 we began to use these modules to introduce green chemistry into nine different courses at Scranton.

In order to lower the “activation energy” for other instructors to green their courses, the modules are available online at our Web site: *http://academic.scranton.edu/faculty/CANNM1/intro.html* (accessed Apr 2004). Materials include an introduction to green chemistry and nine green chemistry content modules. The modules include Notes to Instructors, and a PowerPoint presentation (both downloadable and for viewing online) to accompany each module; an introduction to green chemistry is also available. We have introduced green chemistry into our organic chemistry sequence through the use of one of these modules and other activities.

Infusing Green Chemistry into Organic Chemistry

Making green chemistry an integral part of the organic chemistry course is very important for several reasons: one in particular is the large audience of both majors and non-majors populating this course. These students will become future chemists, policy makers, health professionals, and business leaders. It is imperative that they are trained to view the chemistry that they encounter with pollution prevention in mind and that they realize that chemists are not only concerned about the environment, but they are also proactive in placing a major emphasis on improving the natural environment.

The Concept of Atom Economy

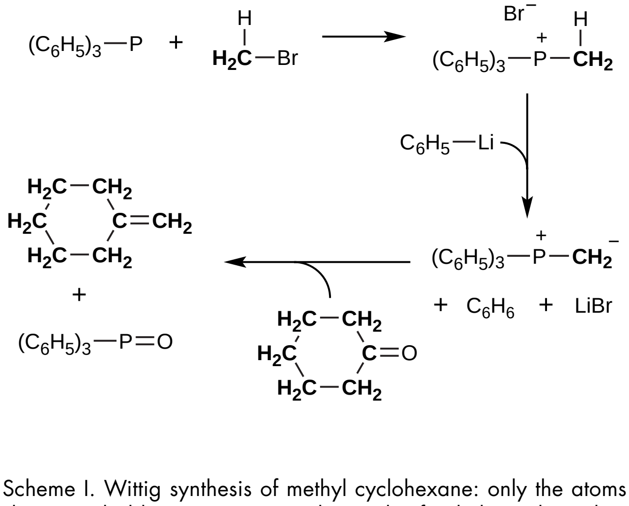
Green chemistry can be infused into the traditional two-semester organic lecture course while adding little additional material to an already overcrowded course by developing the concept of atom economy during a discussion of the four major types of organic reactions (substitution, elimination, addition, and rearrangement).

We precede the discussion of the concept of atom economy with a concise, Web-based module, Introduction to Green Chemistry *(8).* The introduction begins with a brief discussion of dealing with pollution by controlling our exposure to toxic substances (accomplished by “command and control" laws), followed by a new pollution prevention paradigm ushered in by passage of the U.S. Pollution Prevention Act of 1990. (This act sowed the seeds for the birth of the green chemistry program at the EPA in 1991.) The introduction module next defines green chemistry, articulates the Twelve Principles of Green Chemistry *(9),* and provides a brief overview of the Presidential Green Chemistry Challenge Awards. This can be done in 20–25 min of class time.

In the typical organic textbook, it is common to display only the organic products (and sometimes only the major organic product). Reactions are routinely not balanced and little attention is paid to inorganic products. The efficiency of a reaction is often indicated by percentage yield but the mass balance is rarely considered. Thus organic chemists are quite myopic and this fault is passed on to our students.

In 1998, Barry Trost won a Presidential Green Chemistry Challenge Award *(10)* for his development of the concept of atom economy. This concept deals with the efficiency of a reaction and poses the question: how many of the atoms of the reactants are utilized in the final product and how many are wasted? This concept can be easily infused into an organic lecture (using a Web-based green chemistry teaching module) while introducing the major types of organic reactions: substitution, elimination, addition, and rearrangement *(11).* It is a simple matter to then ask students to consider the atom economy of any reaction they encounter. This gives them a much greater appreciation for the fate of the reactant atoms and how efficient a reaction is. Because this exercise in atom economy is coupled with the introduction of the four basic types of reactions this takes little additional class time and blends nicely with the topic.

The concept of atom economy may also be applied to a synthesis. One very informative example of this is the application to a typical Wittig reaction. Although Wittig won the Nobel Prize for his discovery of this reaction, one quickly realizes from an atom economy standpoint that this reaction is less than optimal. For example, the Wittig synthesis in Scheme I has an atom economy of 18% (only the atoms shown in bold are incorporated into the final desired product).



Scheme I. Wittig synthesis of methyl cyclohexane: only the atoms shown in bold are incorporated into the final desired product through this substitution reaction.

Ibuprofen is a widely known and familiar substance, so the atom economy of the synthesis of ibuprofen is a popular illustration of this concept. The old Boots Company synthesis of this compound demonstrated about 40% atom economy. The BHC Company won a PGCC award for a new synthesis *(12)* of ibuprofen that produces 77%–99% atom economy *(6, 11).*

The concept of atom economy is even more suited to presentation or reinforcement in the laboratory component of the organic course sequence. Our students are introduced to atom economy in the first synthetic reaction that they perform. Most lab instructors require the students to calculate the theoretical yield of the synthesis being performed. The students then compare their actual yield to the theoretical value and report a percentage yield. This makes the students aware of the efficiency of the synthesis and, in some cases, their own experimental technique! However, the concept of atom economy can be used to demonstrate that even the most efficient synthetic procedure may have unintended negative environmental consequences.

A table of atom economy can be included in the calculation section of the lab report and the students can use it to calculate the percent atom economy of the reaction being performed. To give a more complete picture of the reaction under study the students can multiply the percentage yield by the atom economy to calculate a reaction efficiency (% yield × % atom economy = % Y·AE). For example, if a reaction had a 90% yield (wouldn't we all like this type of yield!) but only a 50% atom economy the reaction efficiency (% Y·AE) would be only 45%. This calculation makes the students aware that less than half of the weight of the reactant atoms is incorporated into the final product of the reaction. So, what appears to be a highly efficient reaction based on percentage yield (one that may earn the student a high grade for technique), is actually an environmentally disappointing synthetic procedure since 55% of the mass of the reactants used is headed for waste disposal.

Students can also be asked to consider possible ways to improve the atom economy. This can be included in the discussion section of the lab report where students typically consider (and often explain) the technical and experimental reasons for their percent theoretical yield. For example, in the Wittig reaction shown in Scheme I students can determine the effect of replacing the bromine with chlorine. They would calculate an improved atom economy percentage. A separate issue would involve a discussion of how this "improvement" would affect the mechanism of the reaction and whether or not it would have a beneficial environmental impact.

The work performed in the organic laboratory affords the opportunity to examine several other aspects of green chemistry.

- Greening the lab course begins with the choice of textbook and experiments. Many of the current texts have excellent coverage of the environmental aspects of the experimental reactions and utilize procedures to minimize toxic exposure and generation of hazardous waste. The lab instructor can augment these by a pre-lab discussion that goes beyond just a safety warning to include information on environmental issues involving preparation of the materials being used in the experiment.

- Lab instructors typically emphasize the hazards of the reactants, products, and solvents associated with the experiment being performed. However, this discussion usually centers on the personal safety of the student and the lab personnel. This can be expanded to include an assessment of the environmental hazards of these materials.
- Students are always instructed on waste disposal in the lab and are required to dispose of solvents, drying agents, byproducts, and so forth in properly labeled containers. Those instructions can be expanded to include information on the fate of those materials once they leave the student lab. Discussions of waste hauling requirements, disposal deadlines, treatment of hazardous waste, and other related topics make the problems of environmental contamination more real to the students.
- Even more important is conversion of reaction waste products into less hazardous or non-hazardous forms. Many texts include directions for neutralizing acids and bases, and provide procedures for simple reactions that may be performed at the conclusion of a reaction to render unused reagents and reaction byproducts non-hazardous, thereby eliminating the need for special disposal techniques.
- Energy requirements for heating and cooling of reactions can lead to a discussion of techniques that minimize the use of energy. Working in groups the students can experiment with shortened reflux times, or lower reaction temperatures. Pooled data on yield versus time and temperature often indicate to the students that the listed reaction conditions are actually overkill. In other experiments students find that a large reduction in heating results in only a small, and acceptable, reduction in yield!
- The sources of the reaction substrates and reagents can also be discussed. In most cases the chemicals used in the typical undergraduate laboratory are derived from petroleum-based feedstocks. The importance of the products of petroleum refining and reforming for organic synthesis can be emphasized as part of a discussion on the responsible use of this non-renewable resource.

Although there are many other ways to infuse green chemistry into organic chemistry courses, using the approach of atom economy offers one of the simplest ways to initiate this process. The discussion of this concept, along with the items listed above, provides students with a greater awareness of environmental impacts when considering the synthesis of a compound.

Green Chemistry and Sustainability in Other Disciplines

It is not only necessary to infuse green chemistry into the chemistry curriculum: we must take an interdisciplinary approach and teach the basic tenets of green chemistry and sustainability to those who are majoring in other disciplines such as business, political science, and philosophy. Although it is scientists and engineers who will practice green chemistry, business leaders will guide the course of companies on the path of sustainability and political leaders will set the tone for government policy on these issues. We are currently collaborating with business faculty at the University of Scranton to explore ways to bring green chemistry principles into classroom discussions of economics, marketing, management, and accounting.

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Note

1. The contributing faculty members include: Michael C. Cann (principal investigator), Trudy A. Dickneider, Timothy Foley, David E. Marx, Donna Narsavage-Heald, and Joan Wasilewski.

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