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Design of a Dynamic Undergraduate Green Chemistry Course

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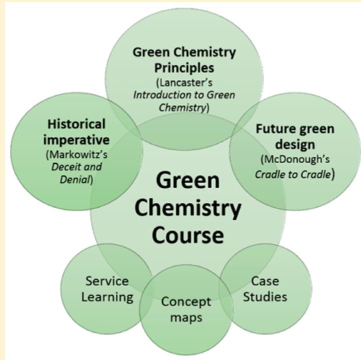
Supporting Information

ABSTRACT: The green chemistry course taught at Westminster College (PA) incorporates nontraditional teaching techniques and texts to educate future chemists about the importance of using green chemistry principles. The course is designed to introduce green chemistry concepts and demonstrate their inherent necessity by discussing historical missteps by the chemical industry, and future design possibilities. Students learn to apply green chemistry principles through case studies and journal article activities, while connecting all of these resources and experiences with concept maps. The final course project requires students to create their own green chemistry educational materials. This nontraditional approach to teaching chemistry provides an opportunity for students to learn in dynamic ways and to be creative in their contributions to green chemistry.



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BACKGROUND

There has been much debate in chemical education literature and at conferences about the teaching of green chemistry topics within existing chemistry coursework or as a stand-alone course.[1−3] Several models of infusing green chemistry into the curriculum have been published,[4−6] as well as examples of development of comprehensive courses.[7−11] While there are advantages and disadvantages to each method, the overall goal of educating students about how to apply green chemistry principles is essential, regardless of delivery mode. Whichever framework works best at any given institution should be championed and encouraged. At Westminster College, a small liberal arts college in northwestern Pennsylvania, green chemistry concepts have been included in general and organic chemistry and a stand-alone course has also been added to the curriculum. While many examples are available in the literature for greening organic laboratories and adding modules to existing courses, there are fewer examples of individual green chemistry courses. The comprehensive introductory green chemistry course at Westminster College has been taught since 2006 and has progressed through many iterations. The course is currently taught with nontraditional teaching techniques and an emphasis on the imperative of green chemistry as the future of chemistry.

COURSE DESIGN

Course Logistics

The 300-level green chemistry course, with an average enrollment of 14 students, is now offered every other year and is a popular elective for chemistry, biochemistry, and environmental science majors. The course meets for 3 h per week in two 90 min blocks without a designated laboratory component. The prerequisite of one-semester each of organic chemistry and quantitative analysis ensure the students have the ability to comprehend research articles and have the vocabulary to discuss advanced green chemistry applications.

Course Theme and Texts

The theme of the present course centers upon the concepts of green chemistry and places these ideas into a context that will convince the students that green chemistry is the only responsible way to practice chemistry. The rational for the course text selection was to provide a main source for concepts of green chemistry (Lancaster's *Green Chemistry Introductory Text*)[12] and then provide two additional texts that (i) demonstrate the necessity for green chemistry based on the historical context of industrial chemistry (Markowitz's *Deceit and Denial*);[13] and (ii) provide motivation for future design possibilities that lack constraints in traditional methodologies (McDonough's *Cradle to Cradle*).[19] To provide context for the necessity of green chemistry, the historical text (Markowitz's *Deceit and Denial*)[13] details detrimental health and environmental effects caused by early chemical industries and discusses the inception of OSHA and the EPA. The historical text is compared with an introductory green chemistry text that provides the framework for learning topics such as waste prevention and designing safer chemicals. Students delve deeper into the green chemistry principles with current literature[14−16] and case studies[17,18] showing the applications of modern green chemistry. While the historical text sets up a

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Table 1. Green Chemistry Topics and Their Related Supporting Texts and Resources

Green Topic	Chemistry Content[a]	Historical/Motivational Context[b,c]	Green Examples and Resources[d]
Green chemistry principles	Ch. 1: Concepts of Green Chemistry	Overview of *CC* and *DD*	Resources: ACS, EPA, Beyond Benign
Green chemistry imperative	Ch. 2: Waste: Production, Problems, and Prevention	Industry's Child and The House of Butterflies (*DD*)	Case study: Ibuprofen synthesis[17]
Green chemistry metrics	Ch. 3: Measuring and Controlling Performance	A Child Lives in a Lead World (*DD*)	Case study: atom economy;[17] *Journal* article: Green star[15]
Catalysis	Ch. 4: Catalysis	Better Living through Chemistry? (*DD*)	Case study: TAML oxidant activators[17]
Safer solvents	Ch. 5: Organic Solvents	Ol' Man River or Cancer Alley? (*DD*)	Journal article: GSK solvent selection guide[14]
Renewable feedstocks	Ch. 6: Renewable Resources	This Book Is Not a Tree (*CC*)	Case study: Cellulose processing[18]
Green design	Ch. 8: Designing Greener Processes	Why Being "Less Bad" Is No Good (*CC*); Eco-Effectiveness (*CC*)	Final projects: case study creation or service learning
Green industry	Ch. 9/10: Industrial Case Studies/The Future's Green	Respect Diversity (*CC*); Putting Eco-Effectiveness into Practice (*CC*)	Final projects: case study creation or service learning

[a]Content delves into the green chemistry concepts from Lancaster's Introduction to Green Chemistry, ref 12. [b]*Historical/Motivational* Context provide a historical reason for the green chemistry imperative from Markowitz (ref 13) or gives examples of future green design from McDonough (ref 19). [c]*CC* refers to *Cradle to Cradle* (ref 19); *DD* refers to *Deceit and Denial* (ref 13). [d]Applications are from a variety of sources as listed and provide a real-world example of current green chemistry examples and resources.

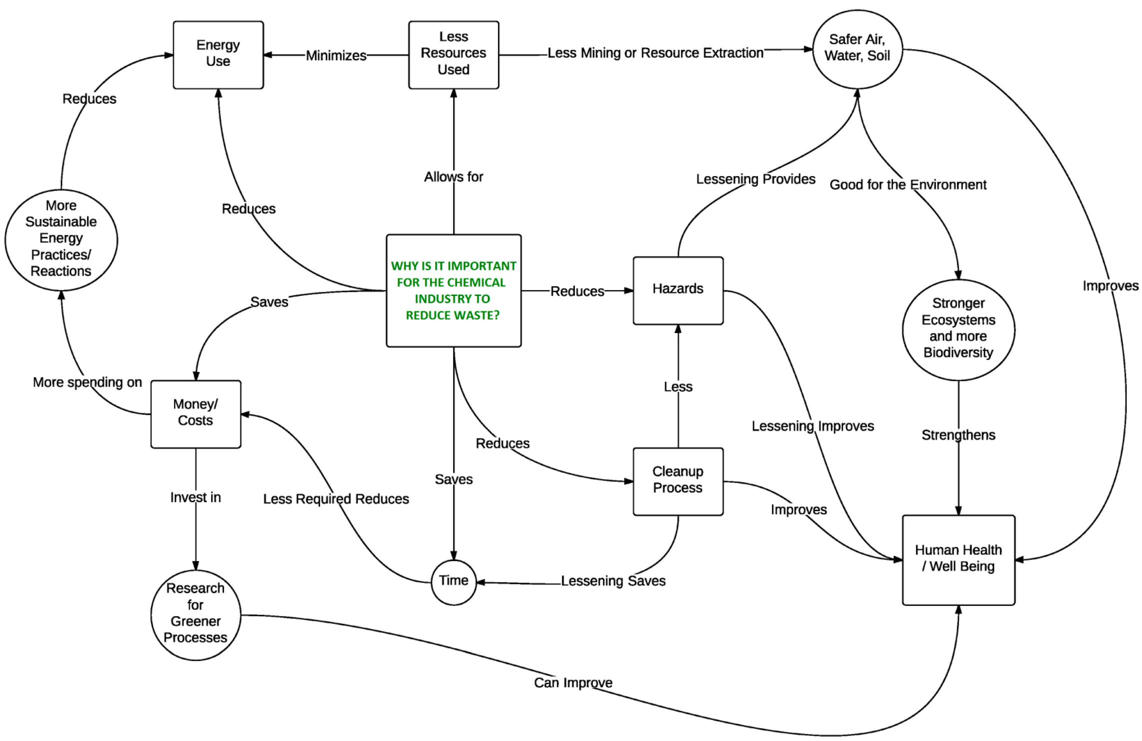

Figure 1. A small portion of a student-generated concept map relating multiple course concepts.

drastically negative view of chemical industry, the course ends with a motivational text, *Cradle to Cradle*,[19] that illustrates that future makers-of-things can be creative and unrestrained by conventional methodologies. Since our students are future creators of chemicals and materials, it is essential that they understand the power they wield in their craft and the obligation they have in decision-making.

The historical or motivational texts are tied into the main concepts from the green chemistry introductory text to provide context for each topic (Table 1). For example, during Lancaster's discussion of problems and prevention of waste, a reading in the *Deceit and Denial* text emphasizes the deplorable effects of lead poisoning. Later in the semester, when discussing renewable resources in Lancaster, readings in the *Cradle to Cradle* book were assigned to show ingenuity in design, such as the topics covered in the chapter entitled "This Book Is Not a Tree".[19] The intentional connection between green chemistry topics and the texts were threaded throughout the course and emphasized by a variety of teaching methods as discussed in the next section.

■ COURSE TEACHING METHODS

Comprehension Gauged by Guided Reading Questions and Quizzes

Understanding that the reading load for this course was quite heavy, students were provided with guided reading questions to help them focus on the main points within each section of the text and how the excerpt related to core course concepts. These

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Table 2. Examples of Nodes and Linking Phrases Used in Concept Maps

Concept Map Question	Node Examples	Linking Phrase Examples
What tools would you suggest to a chemist who wants to do an alternatives assessment for a solvent in their large-scale purification scheme?	Economics	Incorporate information from
	Life cycle assessment	Better than
	EPA	Influenced by
	Green matrix/star	Validates
	Team of chemists	Produces
	Green Screen	Measures
	GSK solvent guide	Ranks
Suppose you are hired to develop a green chemistry program surrounding the development of an insecticide. Which professionals would you recruit to be involved in your program?	Chemist	Researches
	Toxicologist	Measures
	Chemical engineer	Designs
	Environmental lawyer	Stays current with
	PR team	Influences
	LCA team	Limits negative effect
	Chemical hygienist	Collaborate with
Project how the vinyl chloride industry may have been different if the ideals of green chemistry and *Cradle to Cradle* were enforced during early production.	Education	More informed
	Cradle to grave	Rather than
	Upcycling	Creates ideas for
	12 Principles Environmental monitoring	Demand application of Leads to

questions were assigned for each of the three main texts and were the basis of much of the in-class discussion. When the application of the concepts was explored using a research article, a short multiple-choice/short answer quiz, given at the start of class, was used to encourage students to come to class having read and understood the article. The quizzes were reviewed immediately in class to initiate discussion and clear up misunderstandings about the articles. The reading questions and quizzes were a significant portion of the grade in the class because reading preparedness directly impacted discussion quality (Supporting Information).

Green Chemistry Application Explored by Using Case Studies and Journal Articles

Associated with concepts from the introductory text and the historical or motivational text, students had additional readings and in-class discussions based on an application of the green chemistry concept, as shown in Table 1. For example, when learning about metrics in green chemistry, Ribeiro's introduction of the green star was discussed as an additional way for students to be able to apply metrics to processes.[15] When learning about solvent choice, the GSK solvent selection guide was referenced.[14] The American Chemical Society *Real-World Cases in Green Chemistry*[17,18] were often referenced as well to show award-winning applications of green chemistry technology. To encourage students to discuss the topics, many of these application type of assignments were completed in groups during class time. Students used open source software (e.g., Google docs) to share their documents and group edit their work. This provided an opportunity for students to work collaboratively using technology.

Connecting Ideas by Using Concept Maps

While the course was designed intentionally to introduce green chemistry concepts in the context of history, current applications, and future design possibilities, the use of student-generated concept maps required the students to apply all of their readings to green chemistry principles. For example, when discussing waste production and prevention, one group of students posed a central question: "Why does the chemical industry need to reduce waste?" and then they linked concepts from the course to answer this question (Figure 1). This was the first time that many of the students had ever used concept mapping in a science course, or quite possibly any course. Resources from Dr. Hal White at the University of Delaware and Dr. Julie Haack from the University of Oregon were consulted to provide a definition and details on how to construct a concept map.[20,21] Small examples of concept maps were shown to the students and evaluation criteria were discussed with the class. This led to creating an evaluation rubric that defined the graded segments of the concept map and described the requirements for each score range (Supporting Information). The use of the concept maps was most effective when groups could work together to brainstorm and edit the content, rather than as an individual assignment.

During the 2 h final exam period, five major course concepts were posed in the form of a question for development of concept maps (some examples shown in Table 2). Prior to the exam period, the students were encouraged to review the entirety of the course material to be prepared to appropriately contribute the group concept mapping exercise. Each student was required to contribute to each map to provided evidence that they learned how to incorporate examples from throughout the course to answer the posed questions. These maps are now posted in our department to provide conversation starters for green chemistry.

■ COURSE FINAL PROJECTS

As a final project, the students could choose to prepare their own green chemistry educational module or participate in a service-learning opportunity to create green chemistry laboratory activities for a local high school. The assignment and rubrics for each of the final projects can be found in Supporting Information.

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Creation of Novel Educational Materials

Because the students had familiarity with case studies based on the Presidential Green Chemistry Awards,[17,18] several students selected to craft a case study that could be used in future green chemistry courses. One case study was created to facilitate the use of the *St. Olaf College Green Chemistry Assistant*[22] and incorporated its use with a current literature article about greening inorganic chemistry laboratories.[23] This tool is a Web site that allows for the analysis of chemical reactions and performs calculations such as atom economy and percent excess. This site also provides links to compare solvents through the EPA Green Chemistry Expert System database. The students in this group created a series of questions to help the class to understand the research article and then used the *Green Chemistry Assistant* to contrast syntheses by a variety of traditional and green metrics. These students also wrote an instructor's key to go along with the case study and reflected on the process of the creation of the learning module. In this reflection, the students mentioned thinking about the other case studies in the course, incorporating as many green chemistry principles as possible into their project, and making the case study interactive and engaging. Evaluation of this project was based on originality, green content and completeness; the project was so successful that it will be used as an assignment in the next green chemistry course taught at Westminster College.

A separate original case study was also created that focused on the production of nylon and the evaluation of the synthetic routes with respect to green principles. This case study required integration of multiple primary literature articles and the ability to understand that green chemistry is not absolute, but often requires trade-offs. The student author is currently exploring publication of the case study to contribute to the body of green chemistry educational materials.

Implementation of Service-Learning through Green Chemistry Laboratories

Two-thirds of the class decided to append high school laboratories to introduce concepts of green chemistry at the precollege level for their final project. With the advantage of an ongoing collaboration between Westminster College and Sharpsville High School (Sharpsville, PA), the students were able to implement their adapted laboratories with high school students. Some examples of experiments included depolymerization of lactic acid focusing on renewable resources, and endothermic and exothermic reactions using a renewable catalyst.[24] Students were required to modify the laboratories to increase the green chemistry content with, at the very least, pre- and post-lab questions. Each of the lab modules was tested among the groups at Westminster College and then implemented with the high school class. During the testing at Westminster, students were able to receive feedback about their experiment and adjust their protocols accordingly. The students were evaluated on the modifications done to the laboratory to enhance green chemistry content; students were also assessed on the constructive feedback they provided to their peers during lab module testing. Successful implementation of at the high school depended on the enthusiasm and ownership taken by the college student in mentoring the laboratory students during the experiments. In general, the high school students were excited to perform a new lab and appreciated the opportunity to interact with college students. The teacher provided feedback that indicated the high school students had an increased interest in the topics learned during this laboratory period. In terms of outcomes, increasing high school student awareness of green chemistry was accomplished. The modification of laboratories by the college students was evaluated by the professor for completeness, clarity, and incorporation of green principles. In future courses, students should be challenged to create all original content, a detailed rubric for grading will be provided, and the high school teacher will be consulted for evaluation of effectiveness of the project.

■ STUDENT PERCEPTIONS

To gauge the student perceptions of the green chemistry course, a pre- and post-course survey was administered to the 2014 green chemistry class of 14 students (Supporting Information Table 1). Prior to the course, 79% of the students replied as neutral or disagree to the statement "I have a good understanding of the concepts of green chemistry", while 100% of the students strongly agreed or agreed to that statement at the conclusion of the course. Additionally, the post-course survey showed that students were able to understand how to use green chemistry metrics, evaluate literature, and understand the importance of all chemists practicing green chemistry.

■ SUMMARY

An undergraduate green chemistry course implemented at a liberal arts institution is presented with Supporting Information provided for more detailed explanation of coursework. In the course, a historical text provided the framework for the necessity of green chemistry, while a progressive motivational text closed out the course with examples of how to think unconventionally about design. These texts were connected to an introductory green chemistry textbook that provided an outline for investigating main topics of green chemistry and students strengthened these connections by creating concept maps. Case studies, literature articles, and the final project encouraged the students to look at real applications of the green chemistry they were learning. The service learning and case study creation projects displayed the progress of student learning and also enabled students to contribute green chemistry educational materials that can be used in the future.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00432.

- Post-course assessment data (Supporting Information Table 1) (PDF, DOCX)
- Course syllabus (PDF, DOCX)
- The final project assignments, concept map grading rubric, example quiz and reading questions (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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