Teaching green chemistry

After a career as a synthetic chemist and polymer chemist in industry, Albert Matlack from the University of Delaware in the USA has developed a course in green chemistry. He had been inspired by reading a report in Chemical and Engineering News *(April 4, 1994, p34)* **on a symposium on Environmental Chemistry Education, which put forward the idea of teaching green chemistry.**

Choosing the material for the course involved making a list of every environmental problem that I could think of that involved chemistry. The next step was to attend the symposium on Green Chemistry at the Washington meeting of the American Chemical Society in August 1994. Putting these two together, along with a lot of journal reading, resulted in the following course[1] outline:

1 The need for Green Chemistry
2 Doing without toxic chemicals (illustrated by phosgene)
3 The chlorine controversy
4 Toxic heavy metal ions
5 Solid catalysts and reagents for ease of work-up
6 Solid acids and bases
7 Separations
8 Working without organic solvents
9 Biocatalysis and biodiversity
10 Stereochemistry
11 Agrochemicals
12 Materials for a sustainable economy
13 Chemistry of longer wear
14 Chemistry of recycling
15 Energy and the environment
16 Population and the environment
17 Environmental economics
18 Greening

Some of the impetus for 16 and 17 came from attending meetings of the Ecological Society of America and the American Association for the Advancement of Science.

Green chemistry is the chemistry of a sustainable future. A sustainable future is one that allows future generations as many options as we have today. The industrial ecology being studied by engineers and green chemistry are both parts of one approach to a sustainable future. On the other hand, environmental chemistry, as taught today, is largely the study of what man has put into the environment and its effect, as well as how to remediate contaminated sites.

Green chemistry is interdisciplinary. When I lecture on waste minimisation, ion exchange resins and zeolites, I sound like a chemical engineer. When I talk about population and the environment, I sound like a physician, When I go into renewable energy, I act like a physicist. The social impact of scientific discoveries is included: two common criticisms of scientists are that their training is too narrow and that they do not consider the social impact of their work. I now read at

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a lot of journals that I barely looked at before, such as *Progress in Organic Coatings*, *Waste Age’s Recycling Times*, *Rubber World*, *TAPPI Journal*, *etc.*, and I look at the catalysis and chemical engineering journals more carefully that I used to. Review articles in the Encyclopaedia of Chemical Technology and Ullmann’s Encyclopaedia of Industrial Chemistry have also been very useful. Gordon Research Conferences on biocatalysis, membranes and zeoloites have also helped.

The course was first given in the spring of 1995, and was taught for the fourth time in the fall of 1998. Since there was no text, I have written one with about 3000 references. There are several messages which I would like students to take home from the course:

- If you don’t use a chemical, you don’t have to buy it and you can’t lose it.
- Green chemistry need not be expensive. If the whole chemical process is rethought and modified, the result may be cheaper.
- It may be not be possible to green every step of the process at once. For example, a recent synthesis of ibuprofen reduces the number of steps from six to three, but still caries out an acylation step with acetic acid and hydrogen fluoride.
  It may be possible to substitute a solid acid, such as a zeolite, for the hydrogen fluoride.
- Each of us is part of the problem, in that we buy cars painted with solvents, have a bathroom in the house, use electricity, use single-use disposable items etc.
- The problems are social and political as well as technological, and are not just economic.
- There is often a hierarchy of approaches to a problem. To illustrate, trichloroethene is often used to clean metal parts and has become a common contaminant of groundwater and the atmosphere. Putting a lid on the degreasing tank will reduce losses to the air. If the tank is sealed whilst in use, the solvent drained and then vacuumed out, and the vacuum released before opening, very little trichloroethene is lost. If the cleaning is done with an aqueous

detergent, then there is no chlorinated solvent to lose. The biggest change comes from altering the manufacturing process for the metal part so that there is no grease to be removed.

The course is taught for three hours one evening a week, to seniors, graduate students, and to people working outside the university who want to keep up with developments. Some of the most interested students are those from industry, who can relate to the subject matter better. One chemical engineer from DuPont would bring in photocopies of papers that he felt would be useful for the rest of the class. Each section has required outside reading and student exercises, which are designed to be more than just plugging numbers into a formula. Students may be asked to give an opinion on a question such as: Is nuclear energy the solution to global warming, or does it have too many problems? I have them go to the local farm and garden supply store to see what is being sold to put on lawns and crops. Then they look up the toxicities of the chemicals and decide what might happen if these substances washed off into the nearest stream. The next step is to consider friendlier alternatives. The course is designed to take them to the frontiers of research in green chemistry, and they are expected to apply what they learn, not just memorise a list for a quiz. A frequent exam question involves a procedure from organic syntheses that uses a lot of different solvents and toxic chemicals. They are asked what might be done to make it greener.

The challenge of a three-hour class is to use enough interactive class exercises to keep the students awake and alert. If done properly, these can help the students learn to speak in public and to lead group discussions. One exercise involves the selection of two discussion leaders by lot to lead a discussion of a paper assigned for outside reading. I have had the class help me list the toxic heavy metal ions on the blackboard, then completed the list as needed. Then each student gets to pick one to report on at the next class. Every student is required to know the material on all the metal ions for future exams. If reports are longer and cover an applications area, then a dry run may be required. About half an hour before the end of the class I often divide the students into groups to work on a real life problem. After about fifteen minutes, or whenever they seem to have stopped working constructively, we put their suggestions on the board, rotating among the group spokespersons. I then add or delete from their list as needed. A modification of this approach seems to be a good way to revise for exams. They are split into two groups, and each student in group 1 gets to ask one question of group 2. I keep score on the board, but if the same person answers two questions in a row, I only award half a point. When group 1 finishes, the questioning and answering is reversed. After alternating a few times, we decide which team has won.

Field trips are possible. These might include visits to a solar house, a farm using sustainable agriculture, a tannery, a plant manufacturing solar cells *etc.* Term papers are also possible. These might take the form of investigative reporting, where the students check companies to see how green their processes are. For both field trips and term papers, the reports should identify what chemicals are being used and make proposals for reducing the use of energy and toxic chemicals etc. The present course does not have a laboratory, but students could profit by having one that introduces them to techniques that they might not encounter in their regular courses. Experiments might include:

> 'the biggest challenge of green chemistry is to get people to adopt it'

- The synthesis, characterisation and evaluation of a zeolite.
- Running a reaction in an extruder
- Using a catalytic membrane reactor
- Adding ultrasound or microwaves to a reaction
- Making a chemical by plant cell culture
- Performing biocatalysis
- Making a compound by organic electrosynthesis
- Running a reaction in supercritical carbon dioxide
- Using a heterogeneous catalyst

Ideally, the students would use a known reaction first, then do one which hasn't been done before. This may help them to write research proposals.

Some of the other faculty are very sympathetic to the course in green chemistry. Others, however, would prefer that their students take 'core' courses such as advanced organic chemistry and organometallic chemistry. My goal is to stop teaching green chemistry as a separate course and instead insert portions of it into all the other chemistry and chemical engineering courses. However, the chance of getting these faculties to take my course so that they can do this is virtually nil. Some faculty members are happy with what they are doing now and couldn't care less about how things are done in industry. Some schools don't even teach polymer chemistry! There is still the perception that the chemistry of industrial processes and of applications is simpler and less elegant than that done in schools. The artificial delineation of disciplines works against interdisciplinary research, although this is where much new knowledge is found. With chemistry, biology and chemical engineering departments in separate buildings, it is not too surprising that cross fertilisation is low.

The biggest challenge of green chemistry is to get people to adopt it. We would like to see it incorporated into every course from high school onwards. We would like to see all of industry embrace it. The reasons that business has been slow to adopt it are not just economic (see, for example, J. Johnson, *Chemical and Engineering News,* August 17, 1998, p. 34). They may involve a perception of risk in unfamiliar methods or a corporate culture that does not reward risk taking or a change so large that the company is reluctant to start. While my course attracts a few students from industry, I need a lot more.

[1] For an alternative description of a course in Green Chemistry, see Terrence Collins, *Journal of Chemical Education*, 1995, **72**, 965.