Chemistry Education Reform in the 1990s

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Background

Chemistry education reform has been with us since shortly after chemistry began to be a formal part of the curriculum. The 1990s was particularly fecund with activities designed to modify, either gently or radically, the ways by which professors teach and students learn chemistry. Reform efforts ranged from elementary school curricula through graduate degree programs, focusing on several seemingly eternal questions: What should be taught? How should it be taught? How to assess if it is taught well? Who should be taught? Who should teach? The latter deals principally with the preparation of K-12 teachers, and will not be considered further here. The American Chemical Society (ACS) publication "*Recommendations for the Education of Chemistry Teachers*" presents guidelines for the background and education necessary to properly prepare high school chemistry teachers.

This essay describes curricular reform initiatives from general chemistry to graduate chemistry programs. Most of the coverage will be on lower-division courses and the areas of high student enrollments– general chemistry and non-science majors chemistry. The coverage is not meant to be comprehensive or exhaustive.

Undergraduate chemistry departments typically offer separate courses to address a wide variety of student audiences. The many-hued curricular palette responds to non-science majors, to allied-health students (nursing, respiratory therapy, etc.), and to natural science majors, a category broadly defined to include chemistry majors, biology majors, engineering students, agriculture students, as well as pre-healing arts majors (pre-medical, pre-dental, pre-veterinary). Some institutions have "prep" courses for under-prepared students, as well as designated honors sections of mainstream courses, neither of which type will be addressed here. Thus, the bulk of Chemistry departments' offerings and students are associated with "service" courses to those who are not majoring in chemistry. Departments, of course, also bear the responsibility to offer lower- and upper-division courses to meet the degree requirements of chemistry majors in ACS and non-ACS approved programs.

Over the past thirty years or so, a downward flow and compression of concepts has occurred, especially into general (freshman) chemistry and organic chemistry. Topics previously dealt with solely in upper division courses or graduate courses became more or less standard fare in general and organic courses; coverage in those courses became much more oriented towards physical chemistry principles and concepts. Though perhaps salutary to chemistry professors (especially physical chemistry professors), such an emphasis did little to increase the numbers of chemistry majors over the past fifteen years and did much to disengage and dissuade many other students taking the lower division courses (general and organic chemistry). Over the past decade, chemistry curricular reform has targeted this disaffection and has attempted to alter not just what chemical concepts are taught, but also to change how and when they are taught.

Small groups, collaborative learning, and peer tutoring have become demonstrably effective alternatives or adjuncts to lecturing in freshman and sophomore courses. Such methods are growing in popularity and also are starting to be used in upper-division classes as well, including analytical, physical, and biochemistry courses.

Reform in Chemistry for Non-science Majors

For quite some time, non-science majors were ill-served by the chemistry course(s) they took. Such courses generally were based on the thermodynamics maxim of "infinite dilution approaches ideality." Under this approach, chemical principles covered in majors courses were simply "watered down" to make them ostensibly more acceptable and palatable to non-science majors. This approach, although applicable to the thermodynamics of solution behavior, offered non-science students little contextual basis for the concepts, which seemed to be little more than a farrago of unrelated facts to be memorized. Presented in this way, chemistry was not an exciting scientific subdiscipline to be studied and understood, let alone remembered and respected.

Within the past decade, more attention has been paid to this rather neglected market. Leaders in this area of curricular reform appropriately point out something even recalcitrant chemistry professors admit: this student audience is the primary source of most of society's "movers and shakers"– policy makers, politicians, lawyers, and business leaders. Because these students likely take only one chemistry course (if any), the course should be one to which chemistry departments pay attention and value, not a course to be a stepchild to "more important " departmental courses. Non-science major chemistry courses need to address issues that demonstrate the vitality and usefulness of chemistry, its impact on daily lives, and the process of how science is done. During the 1990s, several books addressing these issues became available. Carl Snyder's textbook *The Extraordinary Chemistry of Ordinary Things*, was one of them, breaking new ground about presenting consumer-based chemical principles. *Chemistry in Context,* an ACS-sponsored project, is the most ambitious and widely adopted curricular reform for non-science majors. The textbook takes a dramtically new approach by teaching chemical principles on a need-to-know basis to address and understand significant societal-technological issues (for example, global warming, stratospheric ozone depletion, nuclear energy, alternate energy sources). The book's detailed Instructor's Resource Guide offers professors a how-to guide for using the *Chemistry in Context* approach. A laboratory manual is also available. A goal of the *Chemistry in Context* authoring team has been that the project stimulate additional curricular change and other books for non-science majors.

General Chemistry Reform

Even though individual general chemistry courses are tweaked on a more frequent basis, the large oscillations of the general chemistry reform pendulum have roughly a twenty year period. Clarion calls for such reform on a major scale and responses to them seem to occur on approximately two-decade intervals. The 1990s has been a very active period of general chemistry reform across the gamut of classroom, laboratory, and assessment changes. A limited, but representative, selection of the many new approaches will be noted here. The 1994 publication *New Directions in General Chemistry* (Baird Lloyd, Editor; copyright ACS Division of Education) is a resource for curricular change generated by the Task Force on the General Chemistry Curriculum. This wide-ranging document provides historiography, philosophy, definitive suggestions, and references related to general chemistry reform.

During this decade, NSF support for general chemistry education reform has had several foci. These emphases include the updating of laboratory instrumentation and facilities, systemic curricular initiatives using multi-institutional and trans-regional involvement, and the application of educational research methods to develop a deeper understanding of how students learn basic and advanced chemical concepts.

General Chemistry Textbooks

Although not particularly appropriate, most general chemistry courses are driven by their textbooks. However, during the 1990s, and especially in the last five years, a number of general chemistry textbooks and course-related materials have broken from the physical chemistry-based coverage, the model developed during the 1960s. The oft-heard (but untrue) "all general chemistry textbooks are the same" comment does not hold up to close scrutiny. Textbooks and commercially available course materials are changing. The different approaches now available include:

1. A course in which solid state and materials science principles form the lattice in which general chemistry concepts are embedded (A. Ellis, *et al Teaching General Chemistry A Materials*

Science Companion American Chemical Society Distribution Office, Department 225 1155 Sixteenth St., NW., Washington, DC 20036).

2. Modular-based materials such as those created by the NSF-funded CHEMLINKS (Beloit College-based) and ModularCHEM Consortia, MC^2 (U.C.-Berkeley-based) projects. The thematic modules, including ones such as air bag design (gas laws and stoichiometry) and stratospheric ozone depletion (chemical kinetics and molecular structure), can be used either as extension/enrichment activities to general chemistry courses, or as the basis for the entire course.

3. The use of in-text and auxiliary (CD-ROM, videodisk, web-based) illustrations that interpret macroscale phenomena through nanoscale-level behavior. These are available with most general chemistry texts published in the past three years. Such "visualizing chemistry" also includes using "sphere equations" and structural formulas to elucidate the balancing of chemical equations and the interpretation of chemical reactions.

4. The persistent and enhanced use of organic and biochemistry moieties to teach general chemistry principles such as bonding, stoichiometry, molecular structure, thermodynamics, and acid-base equilibria (J. Moore, *et al The Chemical World 2ed*). In this way, organic chemistry and biochemistry are integrated throughout the textbook, rather than being "ghettoized" into separate chapters at the end of the book (which normally are not covered). Field testing is being completed on an ACS-sponsored general chemistry textbook and laboratory program that utilizes organic and biochemistry topics.

5. A lectureless format using a guided inquiry approach (R. Moog and J. Spencer, Franklin and Marshall College, and others).

6. An alternative approach to descriptive chemistry different from a systematic coverage by chemical family of the occurrence, properties, and uses of selected elements. The new approach, present in several textbooks, integrates socio-technological topics (including global warming, stratospheric ozone depletion, and consumer-based products (synthetic polymers, solid-state electronics, petroleum-based energy) as ways to illustrate and apply chemical principles throughout the textbook rather than in isolated chapters, which too easily can be avoided.

General Chemistry Laboratory

The overall approach of a significant number of laboratory programs remains based on laboratory exercises that validate selected chemical principles already covered in lecture, rather than being actual investigations involving an unknown item to be determined. In other approaches, students use a carefully prescribed procedure (the so-called cookbook style) to evaluate an unknown quantity (see Abraham, M. *et al* "The Nature and State of General Chemistry Laboratory Courses Offered by Colleges and Universities in the United States", *J. Chem. Educ.* **1997**, *74,* 591-594). Still others, particularly Melanie Cooper (Clemson University), have developed project-style experiments in which teams of students in large-enrollment sections gather data that are then shared collectively to reach conclusions regarding the related questions to be answered. The innovative approach taken by R. W. Ricci and colleagues (The College of the Holy Cross) is for laboratory investigations to drive the lecture portion of the course ("A Laboratory-Centered Approach to Teaching General Chemistry, *J. Chem. Educ.* **1991**, *68*, 228-231). In this way, chemical concepts are developed from laboratory investigations that answer leading questions.

General Chemistry Assessment

Educational theory suggests that the first step in constructing a course or curriculum should be to determine how the material to be presented will be assessed (What has been learned?). The assessment method(s) then establishes the course content and manner of presentation. In general, chemistry professors reverse the process– content first, then assessment of learning (lecture quizzes, examinations, portfolio analysis, oral presentations, writing assignments, laboratory quizzes, etc.).

There is a growing awareness among general chemistry professors that merely asking a student to correctly calculate an answer to a quantitative problem does not accurately measure the student's understanding of the underlying chemical concepts associated with the problem. With many traditional-style questions, students can rely solely on an algorithmic approach to solve problems correctly, with little or no awareness of the important interrelationships among the associated chemical concepts. Educational research has studied this concept learning *vs* algorithmic problem solving to better understand and evaluate how students learn chemical principles (Sawrey, B. "Concept Learning versus Problem Solving: Revisited, *J.Chem. Educ.* **1990**, *67*, 253-255; Pickering, M.; Herschbach, D. "Making Grading Less Painful", *J. College Sci. Teach*, **1991**, 378-380; Nakhleh, M. *et al* "Narrowing the Gap between Concepts and Algorithms in Freshman Chemistry", **1996**, *73*, 758, and others). The ACS Division of Chemical Education Examinations Institute, through its General Chemistry Examinations Committee, has responded to alternative assessment by creating two different general chemistry examinations– a concept-based exam in addition to a more traditional one. Concept-based questions are also beginning to appear in reform-style general chemistry textbooks. Such questions require students to assess data sets, diagrams or symbol-rich sketches (or create them), graphs, or web-based materials, rather than simply "plug-and-chug" their way to an answer.

Organic Chemistry Reform

Overall reform efforts in organic chemistry lag behind those in general chemistry. A major organic chemistry reform, now more than a decade old, has been the shift from macroscale to microscale-based laboratory experiments. This change reduces waste, cost, disposal, and space requirements, while increasing the need for enhanced laboratory technique. Organic professors still opt to include some macroscale or semi-microscale level experiments so that students gain experience with several different technique levels.

Organic textbooks vary in their order of topics and emphases. However, the textbooks continue to be voluminous, in spite of calls to reduce their size. Some see voluminous texts as an advantage that allows instructors to pick and choose from a wide variety of topics so as to customize courses to their liking. Some newer textbooks have begun to include biological and/or biochemistry-based material, in recognition that the majority of organic students are biology and pre-med majors, not chemistry majors. Electronic media– CD ROMs and molecular modeling software– have revolutionized how organic students can study topics such as stereochemistry, reaction mechanisms, and spectroscopy.

Analytical Chemistry Reform

Remarks here are restricted to the teaching of quantitative analysis, an area where the balance between fundamentals and "skills" continues to be a major issue. As noted in the 1998 report of NSF-sponsored workshops "Curricular Developments in the Analytical Sciences", questions also remain about what techniques to emphasize and de-emphasize. The report (http://www.chem.ukans.edu/analyt_curricular_dev) includes case studies in analytical chemistry reform at the undergraduate and graduate levels.

Recent reform efforts in analytical chemistry have focused on moving away from the traditional course coverage and laboratory experiments. A recent survey (C. Dorey, private communication) found that in the majority of institutions polled, the type and nature of quantitative analysis experiments have changed little over the past 50 years, in spite of periodic, rational calls for change. The current new direction involves efforts to change both the lecture and laboratory components of quantitative analysis by using problem-based and context-based learning. Each approach espouses the use of real-world samples and the application of a systematic methodology to their analyses, including the use of today's technology in the classroom and laboratory.

Physical Chemistry Reform
The physical chemistry curriculum recently has been a hot bed of reform initiatives after decades of stasis. Lecture as well as laboratory components have been reformed. The lectureless class/guided inquiry approach has been introduced by Theresa Zielinski (tzielins@monmouth.edu), Rick Moog (r_moog@acad.fandm.edu), and others. More conceptual and applied questions have been developed through the ACS Examinations Institute Physical Chemistry Examinations Committee.

Computer software and hardware advances have made powerful tools available to students and professors alike. In particular, the use of Mathcad has enhanced the ease, minimized the time, and enlarged the range of problems accessible for students to investigate and solve. There is an active Mathcad website dedicated to this purpose (http://www.monmouth.edu/~tzielins/mathcad).

NSF has funded a five-year grant to develop on-line interactive cooperative learning exercises for physical chemistry. The exercises will be based on contemporary topics that enhance the relevance of physical chemistry. A detailed assessment of the project will also be done (Additional information can be obtained from Theresa Zielinski).

Biochemistry Reform
A biochemistry emphasis is one of the options available in chemistry departments approved by the ACS Committee on Professional Training (CPT). Some chemistry departments offer one or more biochemistry courses as part of a chemistry major. Other departments do not, but may allow chemistry majors, as part of their major program, to take a biochemistry course in a biology or biochemistry department. For ACS-approved departments, this situation will change due to the ACS Committee on Professional Training's new guidelines regarding biochemistry. Beginning in 2005, all ACS-certified graduates must have the equivalent of three semester hours of biochemistry. This requirement can be met by a three-credit biochemistry course or by integrating its equivalent into the required core. If the latter approach is taken, the biochemistry material should be distributed among introductory and more advanced core courses. Three areas in particular are to be addressed: (1) Biological structures and interactions that stabilize biological molecules; (2) Biological reactions; and (3) Biological equilibria and energetics. More information regarding this new requirement can be obtained at www.acs.org/cpt/hp.htm.

Reform of Doctoral Education in Chemistry
The American Chemical Society has had an abiding interest in the education of chemists, not just at the undergraduate level, but in masters and doctoral programs as well. Most recently, ACS Presidents Ned Heindel and Ronald Breslow held an invitational conference and a colloquium to examine the nature and implications of doctoral education in chemistry. An outcome of ACS President Ned Heindel's 1994 colloquium "*Shaping the Future of: The Chemical Research Environment in the Next Century*," was the establishment of a task force to respond to conclusions drawn from the colloquium. Two major conclusions reached at the colloquium were that there are too many chemistry Ph.D. programs and that the curriculum for doctoral education needed substantial modification. The full report of the presidential task force, "*Employment Patterns of Recent Doctorates in Chemistry*," is available on the ACS home web page at http://www.ChemCenter.org. In 1995, ACS President-elect Ronald Breslow held an invitational conference to discuss doctoral education in chemistry. The conference participants included

representatives from the chemical industry and from graduate programs that together produce 20% of the Ph.D. chemists in the U.S. The conference resulted in a statement of "best practices" that can serve as guidelines for what doctoral education in chemistry should accomplish and how such goals might be achieved. Dr. Breslow delineated the goals and practices in a *Chemical & Engineering News* article (December 11, 1996, pp 65-66).

Conclusion

The 1990s have been an extremely active period for reform in chemistry education at all levels. Federal funding, software and hardware developments, electronic media, educational research, and American Chemical Society initiatives have all served to catalyze and to bolster such reforms.