The University of Michigan Undergraduate Chemistry Curriculum
1. Philosophy, Curriculum, and the Nature of Change

Seyhan N. Eḡe, Brian P. Coppola,* and Richard G. Lawton
Department of Chemistry, University of Michigan, Ann Arbor, MI 48109-1055

Narrowing the Gap between How We Understand Chemistry and How We Teach It

In 1989, we instituted a new undergraduate chemistry curriculum designed to capitalize on the strengths of mechanistic organic chemistry, a powerful model that allows chemists to make predictions about reactivity for an astonishingly large number of substances. The organic chemistry faculty at the University of Michigan have taken responsibility for instructing first-year students in a two-term course called Structure and Reactivity, the first term of which serves more than 1200 students each fall semester. This course satisfies the introductory organic chemistry requirement for chemical science majors, biology majors, and premedical students. Approximately another 1500 students who need an introductory chemistry course, especially engineering students, enroll in a one-term course called Chemical Principles that can precede entry into the Structure and Reactivity courses. By using the model of contemporary mechanistic organic chemistry, students in the Structure and Reactivity courses are immersed in a mature subject area of chemistry that uses a rigorously defined descriptive basis for relating observed reactivity to molecular structure. Our instructional objective is to have students come to know the powerful conceptual unity that allows professional chemists to understand unfamiliar results according to a few well-refined principles and give them enough examples from which to create analogies.

In our view, incoming university students who demonstrate some degree of chemical literacy do not need a year of introductory physical “general” chemistry followed by a year of “sophomore organic” chemistry. Many important concepts typically taught in general chemistry come up during exploration of the structures and reactivity of organic compounds and of the inorganic species that interact with them. Isn’t it possible to teach bonding, VSEPR, polarity, physical properties, the periodic properties of elements, acidity and basicity, oxidation and reduction, energetics and kinetics using organic as well as inorganic structures? Oxygen, nitrogen, sulfur, phosphorus, silicon, boron, the halogens, and many transition metals are very much a part of “organic chemistry”. What is necessary is a context in which this rich chemistry can be explored in ways that revisit a few important themes throughout an entire year and which provides opportunity for students to practice these themes with increasing understanding and sophistication. Such a context is found in mechanistic organic chemistry because it is the area where a structural molecular approach and mechanistic rationalization of reactivity are most highly developed.

The idea that such a context be used to introduce chemistry is not new (*1*). J. S. Guy at Emory University in 1927 called for organic chemistry to be the introductory course (*1b*). In the 1940s Leallyn Clapp (*2*) instituted a curriculum based on organic chemistry in the first year at Brown University. Organic chemistry has served as the first course for chemistry majors at Bucknell University for many years (*3, 4*). At several other schools—most prominently Trinity University (*3*) and the University of Utah (Parry, R. W., University of Utah; personal communication, 1994), but also others (*5*)—students start organic chemistry in the second term of their first year, as do about half of our students.

As chemists, we are responsible for answering fundamental questions about the material world. What is it? How much of it is there? Where might it have come from and where might it go? How fast did it get there? How do I know? Students should gain insight into these questions as they move from course to course. Much of the work that professional chemists do falls into two categories: they design and prepare new molecules; and they design, manufacture, and use instrumentation to perform chemical analyses. To us, conventional chemistry instruction is too self-referential, drawing too much from its own traditions and too little from the more authentic standard of what chemists actually do. In describing the path that we have taken to address these issues, we intend to inform rather than to prescribe. We will describe an evolving culture within a large academic department and university. We will also describe an evolving curricular program, but do not suggest a one-time “fix” intended or recommended for export. We hope that sharing our experiences and organizing principles will enable other science educators to create useful curricular analogies that draw from their own experiences, strengths, and academic culture.

We want our readers to understand the value of consciously and explicitly linking what we know about chemistry with what we do in the classroom. Although it is possible to adopt the course design or examination practices of someone else, the inconsistencies that arise when philosophy and practice are in conflict result in the very dissonance we are trying to address. For example, many instructors have honestly adopted problem-solving and critical thinking as instructional objectives and use this language as a great “first day of class” pep talk. Unfortunately, little that occurs on days 2 through 40 is related to these higher order objectives. Why is this connection so difficult to achieve? Chemists possess mastery of their subject (content knowledge); but knowing how to blend knowledge of the content of a course with higher-order pedagogical objectives goes beyond simple mastery of the subject matter. It includes insights into how learning the subject matter fosters critical skills and which of many examples or strategies are best suited to develop such skills in students. This additional ability of instructors is called pedagogical content knowledge (*6*). Our struggles to achieve such knowledge for our introductory courses will be a large part of our story of curricular change at the University of Michigan.

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*Corresponding author.

We have organized a set of principles and practices, which we recognize as being inevitably interdependent, into a story. In the first of two papers we will describe:

- our underlying philosophical viewpoint and objectives
- design of our courses and the curriculum
- the culture of change

In the companion paper, we will add:

- instructional strategies
- assessment and evaluation practices

Philosophy

What Is Your Philosophy of Instruction?

The content and the methods of instruction of any course convey messages about philosophy and values, whether or not the course instructor consciously subscribes to such a philosophy and value system. For example, whether or not it is the overarching intent of instructors in general chemistry courses, many students come away from such courses with the conviction that chemistry is the science of mole problems and significant figures. In designing our new courses, we believed it was necessary to state the philosophical goals and values that we wished to convey to students and use them explicitly to provide the context in which to embed the subject matter. Three ideas guide us:

- Chemistry is a liberal art and should be taught as such.
- Knowledge is constructed, not recorded, by learners.
- Faculty and students are both learners; faculty are more expert, whereas students are apprentices.

Chemistry as a Liberal Art

"Chemistry is a neglected 'liberal art;' neither admission nor graduation requirements reflect its place or value in contemporary life, or its intellectual worth." So says *Tomorrow*, the report of the task force of the American Chemical Society for the study of chemistry education in the United States (*7*). "Science is one of the liberal arts and should be taught as such" proclaims a report from the American Association for the Advancement of Science (*8*). What is a liberal art? The best definition that we have found was given by Roger B. Smith, then Chairman of General Motors Corporation, speaking in October 1985 at the University of Michigan. He identified the following skills and mental processes required of today's managers as those acquired and sharpened in the study of the liberal arts.

1. Individuals are trained to recognize recurring elements and common themes.
2. They are trained to see relationships between things that may seem different.
3. They are trained to combine familiar elements into new forms.
4. They learn to arrange their thoughts in logical order, to write and speak clearly and economically.
5. They learn to tolerate ambiguity and to bring order out of confusion.
6. They are accustomed to a relatively unstructured and unsupervised research and discovery process and feel comfortable with nonconformity.
7. They have insight into the fit of form with function.
8. They have learned "sideways" thinking, the cross-classifying habit of mind that comes from learning many different ways to look at things.
9. They have learned to replace confrontation with cooperation and the principles of conflict resolution.
10. They have learned the importance of intellectual integrity, social responsibility, and ethical commitment.
11. They learn that the effective management of change comes from the habit of being receptive to new information, to new paths to traditional goals, even to new goals.
12. They have learned to uncover truths in many forms, and that an answer need not be final.
13. They need to see the worth of the impact of what they do, to understand its place in the larger schemes of things.
14. They learn about the kinds of creativity that leads to visionary solutions.

As chemists, do we recognize these attributes? It does not take much imagination to see how the study of chemistry sharpens the skills described by Roger Smith. The periodic table is an exercise in recognizing "recurring elements and common themes", in seeing "relationships between things that may seem different". Chemistry trains students in the logical and precise use of a symbolic language that is new to them. The difference in chemical properties between bromine, bromine atom, and bromide ion, for example, requires that we be clear which one we mean and that we use both verbal and symbolic language correctly to guide our thinking.

In the list of educational attainments fostered by the study of the liberal arts, however, we see no specific advice on any particular content. Instead, we are reminded that we, as chemists, must make sure that our instruction in chemistry addresses the development of these skills. Knowledge of how we construct our own understanding of the subject matter is an essential but insufficient facet of pedagogical content knowledge. Another important aspect is the skill to make instructional choices that allow students to develop liberal arts skills while they master the subject matter.

The study of mechanistic organic chemistry is particularly well suited for development of the kinds of mental processes extolled by Smith. A course content that repeatedly brings students back to the same arguments about a few principles in the context of the increasingly complex structural features found in carbon compounds fosters development of skills in qualitative reasoning typical of the liberal arts. Students begin to see how "to combine familiar elements into new forms", to engage in the kinds of "sideways" thinking that comes from learning many ways to look at things, and to experience "the fit of form with function". Any student who does not develop a tolerance for "ambiguity" and an ability to "bring order out of apparent confusion" has trouble mastering organic chemistry.

The Conflict over (Covering) Content

How often do we make clear to students the liberal arts skills that we use in our own mastery of our subject, and promote their development? This question was raised by Truman Schwartz at the Symposium on the 50th Anniversary of the Committee on Professional Training. He said (*9*),

> The medium of chemistry is the method: laboratory exercises, problem solving, research. But chemistry is more than chemicals; an understanding of how chemistry works is even more important than knowledge of the facts of chemistry. The modus operandi of chemistry—the way in which chemists think and work—is probably the most stable part of our discipline. It

> is the most important feature we can teach. Yet where in the CPT guidelines is this need addressed?

Glenn Crosby at the same symposium also spoke of the importance of process (*10*):

> I recommend that we ask departments to analyze their core curriculum from the standpoint of process not just content. We must analyze our curricula to find out whether we are requiring students to think critically. We must put inquiry back into our course structures and teach the strategies that a chemist or any thinking scientist uses. If we do so, we will find that many of the topics we believe are sacrosanct are really not important at all.

This call is a reminder of the tendency to confuse superficial or cosmetic changes, which are relatively easy to make, with the much more difficult changes needed at the core of the belief systems of the instructors.

Over the years a number of the organic chemistry faculty in our department had developed ways of teaching organic chemistry that emphasized general concepts and patterns of mechanistic similarities underlying the factual content of the subject. This methodology will be discussed more fully in the accompanying paper (*11*). Students responded positively to this way of learning. In many instances they said they had learned much more than the content of organic chemistry: the skills they developed in analyzing relationships, reasoning by analogy, seeing patterns, sorting out the relevant from the irrelevant in solving problems, translated to work in other courses. They were often surprised to make this discovery about themselves. The more feedback of this sort we got, the more clearly we saw the necessity to make development of such (liberal arts) skills an explicit part of our teaching. It also became apparent that the same methods applied to a somewhat modified content would be ideal for a first-year course.

The philosophical underpinnings of a new curriculum thus became *attention to the processes by which content is conveyed to and understood by students*, even if this requires cutting back on factual information. It is hard to make such a change because we define ourselves professionally by our knowledge of our discipline and our individual subdisciplines. Our uneasiness arises from an erroneous model that pits content against process as if they are mutually exclusive poles at opposite ends of a line. We find it more useful to put content and process on intersecting axes that create regions where the two interact with each other (Fig. 1).

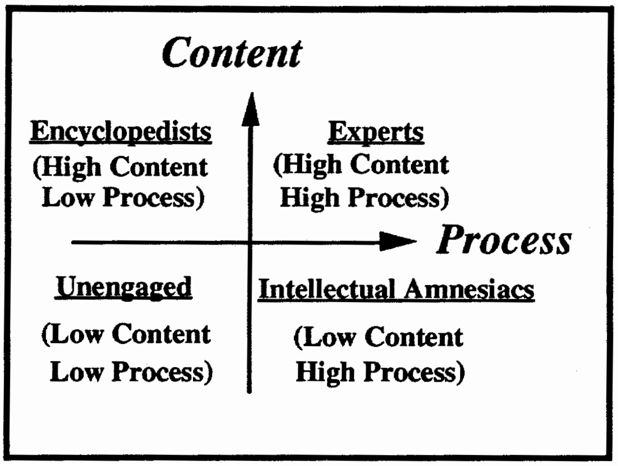

Figure 1. Resolving false dichotomies by a crossed-quadrapolar model.

The factual content of chemistry has expanded into many areas. There are scientists doing chemistry who call themselves by other names (molecular biologists, materials scientists, etc.). We cannot teach, and students cannot learn, all the content necessary for everyone who will use chemistry professionally. We must concentrate on aspects of chemistry that will give students the tools to recognize chemical problems when they see them and to know where to find data, how to analyze data, and how to use data to solve problems, so that they become confident, lifelong learners. The particular content becomes the context in which these skills are developed. Research into learning supports the position that development of such skills is best accomplished not by broad survey courses but by intensive immersion in one area (*12*).

Constructivism

How do scientists think? What is “science”? Robert Oppenheimer (*13*) created a beautiful analogy for the natural sciences by describing science as an edifice that exists and is elaborated only by virtue of the activities performed by laborers as they construct room-after-interconnected-room. All students, whether they will be scientists in the future or not, should be empowered with the image and experience of themselves as active participants in the generation of knowledge.

Cognitive scientists tell us that real learning occurs only when students are actively engaged in the process of “constructing” their own knowledge (*14*). While constructivist epistemology has become a popular and powerful way to think about designing science instruction, we concur with Michael Matthew’s view (*15*) that constructivism is not a revolutionary postmodern invention. It is simply classical empiricism combined with 20th century relativism and given a new name. Constructivism is the way we do science. Our overriding instructional goal is that we be as honest as possible with the realities of our science whether in the classroom or in examinations. If we do this, we naturally draw from and demonstrate the constructivist nature of scientific practice.

Being “honest” in teaching, however, does not mean that every state-of-the-art nuance has to be revealed to beginning students. Being honest means making an explicit inventory of the assumptions and boundaries within which we are operating. Craig Nelson (*16*) uses a wonderful example to make this point: squaring up the sides of a building under construction with two plumb line measurements assumes, like it or not, an operational flat earth model!

As a result of our instructional goal of fostering the construction of knowledge by students, we have reached an inescapable conclusion: introductory chemistry courses should open up a large picture of chemistry as one of the many ways to construct a world view as part of a liberal arts education. Students should have many opportunities to integrate the chemist’s world view with the rest of their emerging intellectual world. Chemists obtain and describe factual information and then tell a compelling story about the world based on those facts. We want to provide firsthand opportunities for students to construct their understanding of chemistry. Learning environments must be designed where the facts and concepts of science are linked to the processes by which those facts and concepts are created, not only in our laboratories, but in the minds of students.

Although mathematical representations of chemistry can be used to accomplish the goals described above, it is too easy to reduce the subject to a manipulation of mathematical symbols and altogether remove the story of chemistry from a chemistry course. As one of our students said after half a term of Structure and Reactivity, “This is cool. I thought chemistry was algebra.” Such a perception is as inaccurate as it is unacceptable, we hope, to all of us. An issue we will address in some detail is that of descriptive and mathematical representations in chemistry and the timing of their use in our program.

Expert and Apprentice Learners

Many students in first-year chemistry courses operate at a concrete level as defined by Piaget (*17*) and are unable to use formal reasoning, especially as it applies to mathematical concepts (*17b*). According to Perry’s model of intellectual development (*18*), many first-year students are still dualistic in their thinking. The most effective teaching occurs when instructors are aware of the developmental level of the students and shape instruction to enhance development of higher-order skills. Effective chemistry instruction should start with concrete models (*17b, 18b*). Even students who are capable of formal reasoning do better if they are given concrete models for abstract concepts. The number of topics should be reduced in order to treat those that remain more thoroughly. The presentation of science should not encourage the idea that knowledge is a collection of facts and the “right answers” are known. Instead, students should be challenged by multiple interpretations of conflicting data (*18b*) and be required to deal with problems that cannot be solved by applying learned algorithms. They should be moved gradually from the concrete to the more abstract. In particular, the teacher’s role should change from that of authority to that of coach and mentor, the “expert learner” who guides the process by which students learn how to learn (*18b, 19, 20*). The rest of this paper and its companion (*11*) will explore how mechanistic organic chemistry serves these pedagogical goals and how they are made explicit in the Structure and Reactivity courses at the University of Michigan.

Curriculum

Structure and Reactivity

Our chemistry curriculum as it was initiated in 1989 is outlined in Figure 2. Students with a strong high school background (as demonstrated, for example, by Advanced Placement Chemistry test scores of 3–5, or performance at or above the 70th percentile on the ACS-NSTA Cooperative Examination for High School Chemistry, Form 1975, Part I) are invited to start Chemistry in Structure and Reactivity. This course immediately engages students in the chemistry of systems of practical and biological interest. At the same time they learn major chemical concepts (such as bonding, dependence of physical properties on molecular structure, energy changes in reactions, acids and bases, equilibrium, and three-dimensional structures of molecules) in the context of mechanistic organic chemistry. In the fall, the first term of the course typically enrolls 1250 students, about half of whom are entering first-year students. In the winter there are about 700 students, and in the spring half-term there are about 100 students. Each week students attend three lectures given by senior faculty and one small discussion session (ca. 25-person) led by a teaching assistant. Students have access to faculty and teaching assistants during office hours and to faculty-run evening workshops and peer study groups (*11*).

The second term of Structure and Reactivity is like the first except that students no longer have the discussion sessions run by teaching assistants. About 1600 students take the second term of Structure and Reactivity each year.

The Lecture Courses

The Structure and Reactivity courses are designed to immerse students immediately into the use of increasingly sophisticated models for molecular interpretation of chemical phenomena. In teaching the courses, we consistently expose students to the thinking and qualitative reasoning processes by which chemists organize data, make predictions, and design experiments. We use class time as much as possible to make explicit the mul-

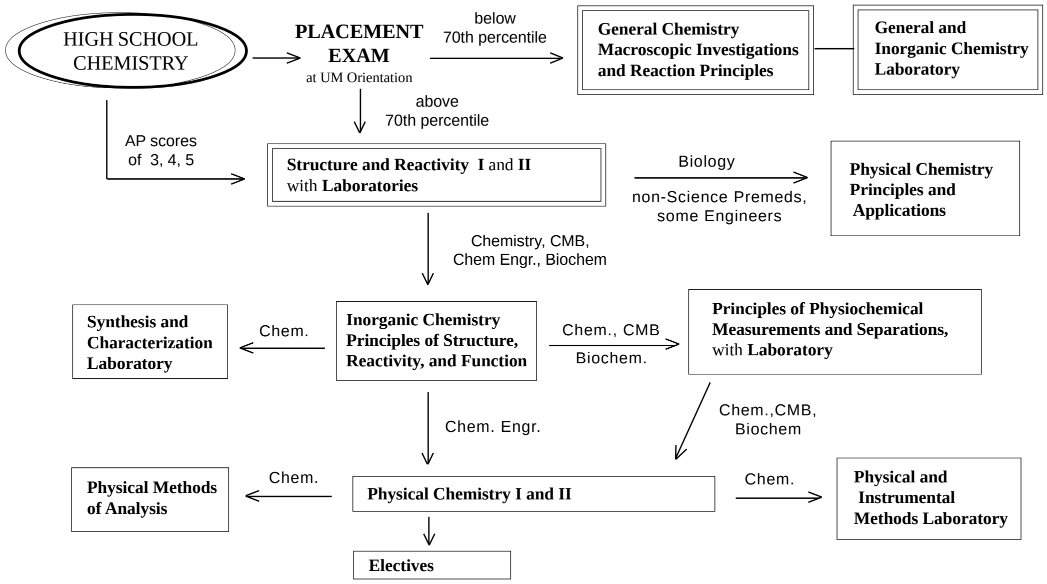

Figure 2. Core of the undergraduate chemistry curriculum at the University of Michigan 1989–1996. Engineers take one term of General Chemistry and lab, or one term of “Structure and Reactivity" and its lab to meet their requirement for accreditation. CMB = Cellular and Molecular Biology.

tiple and flexible ways in which we select and combine evidence to explain chemical properties and predict properties of species with which we are unfamiliar. We stress the processes by which chemists develop models in order to rationalize chemical phenomena.

Thus in lecture, the principles of structure and reactivity provide a vehicle for developing critical thinking and problem-solving skills. For example, stereochemistry is introduced using a case-analysis approach. Learning stereochemistry requires acquisition of a number of skills. Visualization of three-dimensional structures and representation of these in two dimensions are two of these. Development of skills in reasoning by analogy is a third. In introducing stereochemistry, we use as cases molecules (i) with no stereocenters, (ii) with one, (iii) with two that are similar, and (iv) with two that are dissimilar. This approach is used because there are no additional cases that cannot be described by analogy to these fundamental ones. The reasoning by analogy implicit in this approach lets students encounter a generically useful skill (case analysis) and develop the confidence to deal with a large number of new molecules.

Emphasis in the first year is on qualitative reasoning. We postpone the more mathematical aspects of chemistry until students have had more calculus. We hope this will attract more students into the area, and that women and minority students, in particular, will find this way of entering chemistry more appealing than the traditional approaches. A first-year course that emphasizes holistic methods of knowing, emphasizes material that is relevant to life, acknowledges the uncertainties in the ways we know, and invites students to join in exploring how we solve chemical problems is more attractive to these students (*21–23*).

We have restructured all courses to emphasize collaboration rather than competition. Students are encouraged to study together, explain their different approaches to problem-solving to each other, and keep in touch with laboratory results from their peers. Grades are assigned on absolute scales instead of on a curve that implies that only certain percentages of students can be excellent. (The average course grade turns out to be B- to C+, depending on the term.) Thus we hope to change the ways in which introductory chemistry courses are perceived as being inhospitable to students (*24*).

The Laboratory Courses

The First Term: Investigations in Chemistry

By the beginning of the 20th century, laboratory instruction had become an integral part of undergraduate science training. For many years, laboratory courses fulfilled a crucial role in the vocational training of future scientists. Today, large numbers of students, many of whom will never actually do laboratory work in their careers, take these courses. Yet in interviews about the goals for their laboratory courses, faculty in traditional programs most frequently cited the development of manipulative skills for laboratory procedures as a primary objective. These goals are reflected strongly in course designs that emphasize professional standards as a basis for assessment (e.g., amount and purity of a substance in a chemistry lab) without the opportunity for the repetitive practice from which expertise develops. For the last 30 years, the discourse on laboratory design has been dominated by a false dichotomy (compare: Fig.1): cookbook (manipulative and procedural skills) vs. discovery (process skills). “Cookbook” and “discovery” can be better understood as related attributes of expertise: to make discoveries but not reinvent the wheel, we all rely on existing information. Procedures can be used either directly or to create analogies.

In revising our undergraduate chemistry curriculum, we took a fresh look at the laboratory experiences that would accompany the new courses. We wanted students to engage in activities consonant with the liberal arts goals set for lecture courses. We wanted to capture the essence of the research experience: the design, implementation, and evaluation of an experiment with an uncertain outcome.

During both terms of the Structure and Reactivity course, students are enrolled in a four-hour weekly laboratory section. In the first term, the 18–22 students in a discussion session of the lecture course comprise a laboratory section. This promotes a small-group atmosphere. Although the first-term lab course has no separate lecture meeting, the 150–200 students who have their lab course at the same hour meet together for the first 30 minutes for a pre-lab discussion. The value of retaining and refining skills in stoichiometry developed in high school is emphasized in the context of titration chemistry and the calculations necessary to set up reactions and determine yields. Quizzes on stoichiometry are given to help students assess their own level of preparedness. In the second term, a lecture section for the lab course provides formal instruction in spectroscopy, chromatography, and more stoichiometry.

To support the independent and open-ended laboratory activities in our courses, students have hands-on access to FTIR and GC instrumentation and can submit samples for 200 MHz FTNMR from the beginning of the first term. About 35–40 undergraduates staff the instrumentation rooms. These students, some with only one term of experience with the course, are responsible for training and supervising the course participants on the instrumentation. Two graduate teaching assistants train and supervise this undergraduate staff.

The following two examples represent activities from the first-term course, Investigations in Chemistry.

Collaborative Identification of Unknown Materials (25). Each student is given a sample of a solid or liquid and asked to find the students who have the same compound. As chemists we compare data collected in the lab with some set of standards, to answer the question “What is this?” Rather than giving students an explicit algorithm for making an absolute identification of a substance, we use the core of this activity to create a problem in relative identification that is a simple inquiry and a vehicle for developing technical and communication skills. The properties of solids and liquids are explored in this manner in our first-term lab course.

One question that arises every term is what constitutes a valid comparison. The melting point data, for example, fall into clusters, so we always hear a version of “Is 156–157 °C on my thermometer the same as 152–155 °C on yours?” A productive iterative cycle occurs as the need for reproducibility causes students to repeat experiments and revise their original reports in the context of new information. The experimental techniques are clearly seen as tools by which data are collected and from which a question can be answered.

Another aspect of an activity based on the “Who has the same thing as I do?” question is that collaboration requires communication. As a group, students must establish procedural norms for collecting data and for reporting and exchanging the data, in order to solve the problem. We can have eight concurrent sections of the course operating with eight different sets of procedural standards and communication strategies.

Lastly, this is a collaborative learning task (*26*). After the group has established its common experimental procedures, individuals are responsible for collecting data on their own substance. As information flows from individuals to the community, smaller collaborations occur spontaneously. Subgroups gather around a common substance, based on the need to build consensus about the properties of the substance they suspect they share.

Properties of Substances: Creating and Separating Mixtures. We contend that the most interesting features of a mixture problem occur in the stockroom: understanding what substances can be mixed and actually be separated later. Students are given 40 substances representing four different classes of compounds (e.g., acids, amines, hydrocarbons, and alcohols). First, they are asked to perform a systematic investigation of the chemical and physical properties of at least three compounds, each from a different category. Then, based on these observations, they must devise a binary mixture and develop and perform a separation that yields materials sufficiently pure for identification. Each student then submits two samples of the binary mixture with a written set of instructions for the separation scheme. The mixtures and instructions are distributed to other class members later in the term. The original author is the expert for a particular mixture and is solicited for advice (presumably in relation to how well the instructions have been written and the procedure has been worked out). The recipient provides a short peer evaluation.

Second Term: Synthesis and Characterization of Organic Compounds

The second term of the course has a more specific emphasis on preparative organic chemistry than the Investigations course. For some of these activities, we have reduced the usual directions found in standard laboratory texts to general objectives and, as others have done (*27*), we give our students a variety of substrates from which to select.

Literature-Based Procedures. For parts of the course, papers from the contemporary literature are distributed. These describe methodological procedures that (i) are timed appropriately for a laboratory period (or periods), (ii) contain 5–10 representative examples, and (iii) are safe within the technical capability of students. An additional set of compounds is proposed as examples not reported in the paper, and students determine whether the technique is successful on the example they select. Many scenarios are created as these questions are explored. For example, we have examined carbonyl addition reactions of organozinc compounds in an aqueous medium (*28*) in place of the traditional preparation of phenyl magnesium bromide. A dynamic cooperative environment develops as addition reactions are worked out by some students while less successful labmates begin to exchange samples and hints to determine whether it is their substrate or their technique that is causing the problem.

General Chemistry, Macroscopic Investigations and Reaction Principles, and General and Inorganic Chemistry: Laboratory

Students whose career objectives require chemistry other than that offered in Structure and Reactivity or who would benefit from a term of college chemistry before they start those courses take a one-term course called General Chemistry, Macroscopic Investigations and Reaction Principles. This course may stand alone or be preparation for more advanced courses. It introduces major concepts of chemistry, including atomic and molecular structure, periodic trends in chemical reactivity, the energetics of chemical reactions, and chemical equilibria. We have about 1500 students in this course in the fall term and another 500 in the winter and spring terms. The course has three lecture hours and one discussion session a week. About half of the students take Structure and Reactivity in their second term. Hence, the University of Michigan no longer offers a year-long introductory general chemistry course. The material normally found in the second term of such a course is found in other contexts.

The Department of Chemistry is committed to helping students whose science and mathematical backgrounds are weak to become proficient in chemistry. The first-term general chemistry course described above has a section reserved for students who would benefit from a small lecture section (ca. 75 students) and more frequent contact with faculty and teaching assistants. This is followed by a similar section of Structure and Reactivity. Emphasis is on learning how to learn in the sciences with special computer-assisted instruction, “Whimbey Pair” (*29*) problem-solving sessions, and frequent quizzes to provide motivation and reinforcement for successful learning.

Many students in the general chemistry course also take a term of laboratory (General and Inorganic Chemistry: Laboratory). This course has one lecture hour and four hours of laboratory weekly. Again, its goal is to involve students in the discovery of chemical principles from qualitative data and to engage them in the kind of scientific thinking that chemists use in their work. Computers and collaborative work are used to pool qualitative data from groups of students using different sets of reagents in small-scale experiments. Students then have to use the class data to arrive at conclusions about the chemical properties of the range of reagents studied (*30*).

Collaborative learning is also part of the lecture course in general chemistry. Students form teams to explore “The Business of Chemistry” (*31*). They prepare a proposal that explores the chemistry and costs of manufacturing a commodity chemical that they will be able to sell at a profit. They submit a preliminary “impact statement” to a “government” to get a “license” to proceed. Their proposal must include considerations of costs of raw materials, overhead, and energy as well as pollution, waste management, and toxicology. Such a project engages students with each other (signs have gone up in our library asking project students to please be quiet!) as well as with chemistry at a deeper level than usual.

Demographics of the First-Year Courses

The demographics of the student populations in the two introductory tracks in our chemistry curriculum for the past five years are shown in Table 1.

It is tempting to dismiss using the content of mechanistic organic chemistry as an introductory course in chemistry by saying that what is possible at the University of Michigan is not possible elsewhere because students come to us with better preparation and higher SAT scores. We contend that what most general chemistry courses attempt to do with perhaps less well prepared students is more difficult, because of the abstract nature of the material, than what we do with our students.

Table 1. Demographics of Introductory Chemistry Courses, Fall Terms 1991–1994

	General Chemistry		Structure and Reactivity	
	Range	Average	Range	Average
Number of Students	1492–1663	1570	961–1223	1110
Male %	56–60	58	57–60	59
Caucasian %	63–67	65	64–71	67
African-American, Hispanic, Native American %	15–18	16	9–11	10
First-Year %	86–90	88	50–61	54
Engineers %	47–49	48	24–26	25
With AP Courses %	8–12	11	34–36	35
High School Ranking, Ave. Percentile	88–91	90	90–92	91
High School GPA, Ave.	3.6	3.6	3.6–3.7	3.7
Math SAT, Ave.	620–640	630	580–660	640
Verbal SAT, Ave.	520–530	520	560–570	560
Math ACT, Ave.	27–28	27	28–29	29
English ACT, Ave.	26	26	26–27	27

For example, it is widely lamented that students do not have adequate mathematical skills, yet we persist in making first-year courses depend on precisely this weakness. “It’s not the chemistry that’s difficult, it’s the math.” Why not bring the chemistry forward and allow time for math skills to develop before calling on them?

In response to our many presentations about the new curriculum (e.g., *32*), we have also heard an objection diametrically opposed to the one above. What we are doing in our first-year courses is too easy (an assessment with which our students would vehemently disagree). It does not have rigor, a term we think has been inappropriately co-opted as the sole province of mathematics. But if we grant for the sake of argument that an introductory course based on mechanistic organic chemistry is “easier” than a typical general chemistry course, why are supposedly less well-prepared students subjected to the presumably more difficult course?

Courses beyond Structure and Reactivity

Introducing concepts usually part of general chemistry in the context of organic chemistry permits second-year courses to emphasize inorganic and quantitative chemistry (Fig. 2). For majors in chemistry, cellular and molecular biology, biochemistry, and chemical engineering, qualitative reasoning about structure and reactivity is extended to a larger selection of elements in the second year in Inorganic Chemistry: Principles of Structure, Reactivity, and Function. For chemistry majors, this course is accompanied by a laboratory course, Synthesis and Characterization, which presents advanced synthetic methods integrating inorganic and organic chemistry.

Students continuing in chemistry, cellular and molecular biology, and biochemistry are now ready for an integrated approach to analytical and physical chemical concepts and a laboratory that emphasizes the collection and analysis of quantitative data. Principles of Physiochemical Measurements and Separations was designed to immerse these students in quantitative chemistry from the viewpoint of analytical and physical chemists and be a bridge between lower- and upper-level courses in those disciplines.

The second-year courses described above have been evolving. A major change instituted in 1996 was splitting the combined physical–analytical course into two parts. One is a lecture course, Chemical Principles, emphasizing topics traditionally found in the second term of general chemistry courses. It is the first of a three-term sequence of physical chemistry courses. The other is analytical chemistry, a coupled pair of lecture and laboratory courses, Introduction to Chemical Analysis and Introduction to Chemical Analysis Laboratory. Inorganic Chemistry now follows Chemical Principles.

A large number of students major in the humanities or social sciences with the intention of applying to medical school. Many biology majors are also in this category. Biological chemists at our medical school were asked what kinds of chemistry students intending to go to medical school would need after they finished Structure and Reactivity. The course Physical Principles and Applications, which gives more quantitative treatment of equilibrium, acid–base reactions, and the gas laws and introduces phase equilibria and electrochemistry, was developed for such students. It is also available to engineering students who need more inorganic and physical chemistry.

Also in 1996, the two terms of traditional physical chemistry taken by majors were transformed into three courses. The first term lecture course emphasizes quantum chemistry, including group theory and spectroscopy, and is accompanied by a computational chemistry laboratory. The second term takes up thermodynamics (classical and statistical), chemical kinetics, solid state structures, and a variety of special topics. Chemistry majors are required to take another course in inorganic chemistry after they have completed quantum chemistry and the computational chemistry laboratory.

Chemistry majors also take Physical and Instrumental Chemistry, a term of instrumental analysis and an integrated instrumental analysis/physical chemistry laboratory. They must either complete an undergraduate research project or take an open-ended projects laboratory, and take at least one advanced elective. For example, 59 of 69 of our 1995 graduates participated in at least one year of independent study; 30 of these worked in research groups for more than 2 years, and 16 presented Honors theses. The ACS Committee on Professional Training has evaluated the new curriculum and determined that it meets its guidelines.

Courses for Nonscience Majors

The Chemistry Department has also experimented with courses addressed to nonscience majors (many of whom already take our mainstream courses, especially if they think they want to go to medical school). Our most successful approach has been in a pair of courses based on the environment, "Our Changing Atmosphere" (Barker, J., University of Michigan; personal communication, 1994) and "Environmental Issues", which takes a case-study approach, using issues that make the news as ways of introducing students to the scientific principles needed to understand them (Hallada, M. C., University of Michigan; personal communication, 1994).

With the School of Education we have developed a set of courses for preservice elementary school teachers, which are taught by a team of a chemist and a specialist in science education. Students are engaged with the content of chemistry in a context that presents the kinds of open-ended questions that they will face in their classrooms. They are guided in exploring these questions on their own so that they develop confidence in their ability to use the available informational resources and can appreciate the multiple layers of meaning in scientific terms. For example, "You have heard the word 'iron' used when talking about hemoglobin in blood and also in reference to frying pans. Is it being used the same way in both contexts? Why or why not?" In the laboratory they develop and share experiments and demonstrations that they would feel comfortable taking into their classrooms. They are learning about methods of teaching science, made concrete by reference to issues that arise in their personal encounter with chemistry. They also participate in a practicum consisting of classroom observation and supervised instruction in the community.

Impact of the Changes on Other Disciplines

Our new courses were instituted after extensive consultation with the other schools and departments that would be impacted by the changes. In particular, discussions were held with the biology department and the Engineering School, since many of their students are in the beginning chemistry courses. The changes made give biology and biomedical students an earlier introduction to the chemistry that is useful to them in biology courses. Engineers are given a choice of two ways to fulfill their ABET requirement of one term of chemistry with lab. Chemical and materials engineers can get an earlier start on the structural and reactivity ideas they need. The inorganic course is also an important component of this training.

The Nature of Change

The Start of Change

If we are to take seriously the idea that students must be active participants in the generation of knowledge, we must rethink what we teach and how we teach it, especially in beginning courses. The Department of Chemistry at the University of Michigan has been in such a process of reexamination for about ten years. The driving forces for this were several. First was increasing uneasiness, reflected at the national level (*4, 21, 33–35*), with the direction traditional general chemistry courses have taken. In 1966 Henahan (*36*) challenged science educators to think scientifically about the pedagogy of science in order to regain a balance in the curriculum, a challenge that is still being issued (*37*). Gold (*38*) pointed to the need for educators to abandon their "content obsession". He maintained that a laissez-faire attitude toward the curriculum has led by default to a flow of chemical facts from the research laboratories to the textbooks to the precollege classroom. New technologies now threaten to bury us with megabytes of CD-ROM information unless we are willing to make some value judgments. In hesitating to do this we are emulating our students, who in response to an examination question are more than willing to tell us everything they know rather than to create a cogent and relevant answer.

Our concern about traditional first year chemistry courses was fueled by results of a study conducted by the Women in Science program at the Center for the Education of Women at the University of Michigan (*39*). General chemistry courses, partly because they are the science courses taken first by the largest number of first-year students, are mentioned depressingly often by both men and women students as the courses that discourage them from continuing in the sciences. The image of science conveyed too often by such courses and how this disproportionately impacts women students have been discussed in this *Journal* (*22*). Similar concerns about introductory science courses have been put forward by Sheila Tobias (*23*). The image of science that students get from many of our courses is not, as we discussed earlier, the image that the working scientist has and does not correspond to what scientists actually do. Nobody gets a Ph.D. in General Chemistry. In fact, the current order in which topics are introduced to students has been characterized as "putting the cart before the horse" (*40*). It seemed urgent to us to design courses that "put the horse back in front of the cart".

Another concern was that an increasing number of students (3% of the entering class in 1978; 9% in 1993) came to the University of Michigan with Advanced Placement scores of 3, 4, or 5. Students with scores of 4 or 5 got credit at the University for a year of general chemistry and were often advised by counselors not to attempt to take sophomore level organic chemistry courses until their second year. A group of students who were prime candidates for future careers in the chemical sciences broadly defined were not taking any chemistry their first year. It seemed to us that many of these students might be attracted to other disciplines before they had the opportunity to experience what chemistry had to offer.

Our department had a unique opportunity for major curricular change in the mid 1980s when construction started on a new chemistry building. Suddenly the discussion of curricular change that had been going on in the curriculum committee for years took on new urgency. Decisions had to be made on how to equip the new undergraduate laboratories and on whether to move the old curriculum into the new building. M. David Curtis, then chairman of the department, decided it was time for a major change and appointed an Associate Chair for Curricular Development (SNE) in 1988. The faculty adopted in principle the suggestions made by its Curriculum Committee for a program that replaced traditional general chemistry with a new approach. This curriculum was phased in starting in the 1989 fall term. A detailed history of this change is in Tobias's book on innovation and change in science programs (*41*).

How Change Occurs

In a particularly cogent essay, "Reforming Again, Again, and Again," Cuban (*42*) puts the cyclical nature of curricular reinvention into historical perspective. To be successful, the process of change in a large department must be embraced by a significant number of the faculty and must be ongoing. It is not possible to "hire in" innovation. In order to say that the instructional culture in a department has changed, the innovation must survive the innovator. Isolating mainstream faculty from innovation will hinder, whether by design or not, their full participation. Certainly there must be individuals who have the energy and insight to spearhead and sustain change. In fact innovation always starts with individual initiatives. In our case, a group of organic chemists started the process of change in their own courses, and that experience allowed the Structure and Reactivity courses to be created.

Once started, change propels itself through the system by way of students who now have different expectations and skills and by faculty who are inspired by what happens in one course to make modifications in another. The departmental structure, must, however, be receptive and encouraging to faculty members who show interest in working on curricular issues. Nothing less than a change in departmental and institutional culture is necessary for major curricular innovation.

Before systematic change took place in the Chemistry Department, each faculty member was asked to identify with one of the following three positions:

- I believe that curricular change is necessary and I am willing to be involved in the process.
- I believe that curricular change is necessary, but I am unwilling to put any effort toward the process.
- I believe that curricular change is unnecessary.

The faculty split three ways, approximately a third falling in each category. The Chair and the Associate Chair decided there was a sufficient core of faculty in all areas of the department to serve as a nucleus for change. This judgment proved accurate.

The first new courses were the Structure and Reactivity courses. While they were being taught in the first year of change, the new courses for the second year as well as the new first term general chemistry course were designed. The process involved small groups of interested faculty, who worked on the individual courses, as well as discussions in departmental faculty meetings.

During the first year the faculty also held a Saturday retreat where interested faculty met to discuss general curricular issues and specific plans for new courses. Several further faculty meetings, especially open-ended evening sessions, and another Saturday retreat in May 1995 have been devoted to questions of curriculum.

Changing Academic Culture

When new faculty join the department, they are introduced to our philosophy and practices with a supportive infrastructure that pairs them with experienced instructors. In a department where curricular issues are regularly discussed and a college whose dean is deeply involved in promoting undergraduate education as a priority, many of the young faculty become engaged in curricular innovation. As they achieve tenure, some of the younger faculty volunteer to help in the substantial revision of a course. The department chair and the dean provide extra support to ensure that the research program of such a faculty member does not suffer during a period of intensive work on curriculum. Part of the cultural change necessary to sustain innovation is the recognition in concrete terms that creativity in teaching can be as time- and energy-consuming as creativity in any other endeavor. In recognition of this, we have received external funding from the Research Corporation for a postdoctoral intern in chemical education, to bring to questions of curricular innovation the kinds of energy and creativity that research postdoctorals bring to research. We have also instituted a program to involve a cohort of graduate students in curriculum development as they participate in a graduate seminar on teaching and learning in chemistry.

Students as Agents of Change

Students are important driving forces in change. From the beginning, they signaled that something significant was happening by signing up as chemistry majors at the end of the first year in larger numbers than ever before. After only one year of chemistry, large numbers of them applied for and got research positions in external Research Experience for Undergraduate programs and in research groups within the department. Since then, the number of undergraduates doing research in the department has tripled. Undergraduates have also provided us with valuable feedback in other ways. In April 1995 in a formal meeting of graduating seniors with the Curriculum Committee of the department and other interested faculty, they talked about their perceptions of the curriculum and the teaching of it and offered suggestions for change. These suggestions were disucssed at the subsequent faculty retreat.

These changes are ongoing, supported by two Chairs and three Associate Chairs for Curricular Development drawn from different disciplinary areas of the department. They have been recognized in the college and have encouraged curricular reform in other departments, as in the institution of new calculus courses in the Department of Mathematics.

Perspectives and Reflection

For us, curricular progress has taken a path as familiar as any experimental activity. The ultimate destination is rarely the one that was predicted. Progress is subject to fits and starts, sometimes revisiting old territory before moving onward. Individual talents, backgrounds, and experience bring unique contributions. Resistance and intransigency are also a natural part of the terrain, regardless of any plan. Philosophical and sociological frameworks impact scientific cultures whether or not they are explicitly acknowledged. Finally, like good experimentalists, we strive to learn from all of our results, and not just from the ones that are consistent with the desired outcomes. Faculty are creative people, motivated by the rewards of intellectual inquiry. We think that by making curriculum development an ongoing and intellectually rewarding part of departmental culture, we can break the need to reform again, again, and again.

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• R. K. Birdwhistell • Roger G. Biringer • James P. Birk • John W. Birks • Viola I. Birss • Muriel P. Bishop • Thomas E. Bitterwolf • Kersey A. Black • John R. Blackburn • Ninian J. Blackburn • G. R. Blakeley • Paul P. Blanchette • Harvey F. Blanck • Ronald L. Blankespoor • Richard A. Blatchly • Rita G. Blatt • Reed J. Blau • John R. Bleeke • Semour M. Blinder • Henry Blount • Syndey Bluestone • Frank D. Blum • Avrom A. Blumberg • Patricia A. Boaz • Andrew B. Bocarsly • George M. Bodner • Elizabeth A. Boeker • Juliana Boerio-Goates • Donald Boerth • Donald W. Boerth • James E. Boggs • Donna Bogner • Paul W. Bohn • James J. Bohning • James A. Boiani • Robert S. Boikess • Philip H. Bolton • Daniel D. Bombick • James M. Boncella • Marcia Bonneau • William O. Boo • Richard F. Borch • Stuart Borman • Erwin Boschmann • Charles B. Boss • Laurence J. Boucher • Philip Boudjouk • Edward A. Boudreaux • Mary Ellen Bowden • Craig W. Bowen • Kit H. Bowen, Jr. • Nathan W. Bower • Peter G. Bowers • B. Gray Bowman • Vernon G. S. Box • Gregory L. Boyer • Joseph H. Boyer • Rodney F. Boyer • Richard E. Bozak • G. Dana Brabson • Michael S. Bradley • Jerald S. Bradshaw • Alan J. Brainard • Anna F. Brajter-Toth • Fitzgerald B. Bramwell • Bruce P. Branchaud • David J. Brand • E. N. Brandt • Stephen E. Branz • Steven G. Bratsch • Manfred Brauer • Robert D. Braun • William H. Braunlin • Diana C. Bray • Clarence H. Breedlove • Curtis M. Breneman • [illegible] • William R. Brennen • Henry C. Brenner • Ronald Breslow • Gregory Brewer • Karen J. Brewer • James H. Brewster • Adrienne A. Brian • Nancy W. Brickhouse • Peter K. Bridson • Martha S. Briggs • Ronald G. Brisbois • Michael A. Brook • David W. Brooks • Jeffrey Brosco •