The University of Michigan Undergraduate Chemistry Curriculum 2. Instructional Strategies and Assessment

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The philosophy and details of the curriculum initiated in Ann Arbor in 1989 are described in our previous paper (*1*). The second part of this discussion presents specific ideas that have been meaningful for instructors and students in our undergraduate chemistry program. We return to the theme of matching articulated instructional goals and objectives with the classroom practices used to accomplish them.

Many attendant dimensions of scientific practice (philosophy, history, linguistics, ethics, and so on) have been systematically dis-integrated from formal scientific education (*2*). We identified three defining goals for instruction that seeks to be more comprehensive (*3*):

1. Course content is used as a medium for students to develop learning skills. If certain skills are best obtained through study of chemistry, then factual information, in addition to its cultural literacy value, is the vehicle by which those skills are developed.
2. The lens on the natural world that is "chemistry" is viewed as but one model of inquiry among many.
3. Faculty must articulate and understand the unifying instructional objectives within the context of the specialized course and how they are matched to instructional and assessment methods. Only chemists can say how learning to solve gas law problems might represent a broader educational goal.

In this paper we describe some instructional strategies that evolved from efforts to connect our classroom (behavioral) practices with our liberal arts objectives for the Structure and Reactivity courses (*1*).

Instructional Strategies

Representing Relationship between Information and Meaning

One skill that defines expertise is the fluid movement between superficial information and deeper meaning. Another attribute of the expert learner is persistence, a key concept in theories of human motivation (*4*, *5*). We agree that learners construct their understanding by seeking and creating larger patterns—by grouping, ungrouping, and regrouping the interconnections among ideas. There is a great deal of intellectual risk in backing away from a perceived or imagined pattern, even if all the pieces do not fit. Worse, students sometimes believe they are incapable of seeing any pattern at all because of a fundamental inadequacy. A person might make the conscious decision not to invest the energy to persist, but that is a different situation. We have observed very capable students who seem to be unaware that they must actively move back and forth between the smaller and larger concepts, constantly checking and rechecking the internal consistency of the picture they are constructing. One important theme in our instruction, then, is to provide the kind of language and examples that students can draw from in order to persist even when the immediate feedback is discouraging. The typical advice that faculty give based on their own experiences is naive ("stick with it") and draws from their own (un)naturally high persistence as learners in chemistry. Individuals do not persist because of their satisfaction with the fight, but because they can envision and believe in a goal that cannot yet been seen (*6*).

Describing our goals to a group of first-year college students is difficult in the abstract. These students lack experience from which to create analogies at the level of intellectual effort to which we allude. Visual puzzles can be metaphors for the persistent grouping and regrouping of data necessary for successful problem-solving or analysis (*7–10*). Whether solving these puzzles or understanding drawings of molecular structure, the brain must draw upon its prior knowledge and ability to fill in what is missing from the literal presentation of information, to create meaning from what can be seen by imagining what is not seen. Chemists, more than most people, base their intellectual work on a representational system (molecular structure) connoting physical objects that cannot be seen (*11*, *12*). We are as comfortable with the notion that "H-O-H" is water as that "T-A-B-L-E" is a table. We understand that letters have represented atoms and lines indicated chemical affinity since before the discovery of electrons, but these are learned associations, not embedded in the use of letters and lines. Bransford and Stein (*13*) use textual passages to make this same point.

In our teaching, we emphasize that understanding the meaning represented by the scrawlings of any representational system requires understanding inferences and implications not present in the symbols themselves. Phrases such as "When I see this, I also see …" or "From the other information present, I infer that…" are a constant feature in our lectures. A simple activity we have used on the first day of class starts by our writing "HI" on the chalkboard. Any answer to the question "What is this?" other than something like "chalk lines (letters?) on the board" draws from prior experience and not from the lesson at hand. "What could 'HI' represent?" is a more accurate way to pose the question. The answer "Hydroiodic acid", we point out, draws from the implications of having a chemist write the letters, whereas "a greeting" or "a portion of the alphabet" are drawn from inferences in which other assumptions are embedded. Faculty awareness of this is critical in chemistry. Students of surrealist René Magritte can teach students of chemistry that "H_2O" is not, in fact, water, but only its representation (*2*, *14*). The attachment of meaning to and derivation of it from information is a feature of all intellectual activities. Therefore, it is critical for instructors to relate how experts assign meaning, which they do not see, by attaching it to or extracting it from information, which they do. In our chemistry course, there is as much a place for Magritte's *La Trahison des Images* ("The Treachery of Images"), with its disarming message *Ceci n'est pas une pipe*, as there is for images of gamboling, space-filling yet two-dimensional molecular repre-

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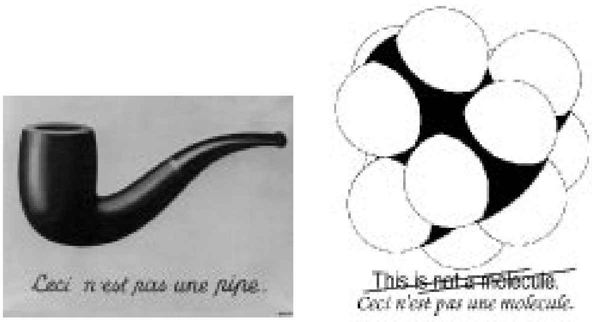

Figure 1. “The Treachery of Images.”

sentations that are no more molecules than Magritte’s pipe is a pipe (*15*) (Fig. 1). In fact, since we introduced the Magritte image and language into the course, students are much more inclined to understand the larger lesson, chemistry’s example being but one among many.

Demonstrating the Role of Teaching in Learning

It is useful for instructors to realize that we ask students to teach us on exams. Whether an exam is written or oral, an instructor takes on the student role as questioner and learner while the student provides answers. Yet opportunities for students to build skills for this role reversal are not provided except at the exams themselves, when faculty tend to adopt the role of arbiters who judge rightness and wrongness. By pointing out to students that during examinations they assume the teacher’s role, we let them confront the need to learn how to express their understanding before the examination.

Our colleagues in disciplines that develop skills for expression (writing, art, dance, theater) recognize the value of the performance studio. This is where skills are displayed to a peer group of learners, usually under the guidance of someone more experienced who critiques and organizes peer review, generally after solitary preparation outside the studio (write a story, fill a canvas, learn the lines). Much high-value learning takes place in the studio because all participants have done something about a common task that carries the results of their individual efforts. Laboratories should fulfill this role of performance studio for chemistry learning, but there are many reasons why this does not happen in practice.

Semi-Structured Study Groups

We provide the opportunity in the Structure and Reactivity courses for students to create performance studios. This idea stemmed from the experience of one of us (BPC) with the University of Wisconsin’s Greater University Tutorial Service (GUTS). We keep two notebooks in a resource room: one for students who want to be study group facilitators and another for those who want to be study group members. Potential time periods and rooms are blocked off and reserved, and students indicate their preferences for times that they can match. A resource person (in our case a teaching assistant) creates study groups of 6–8 participants and 1–2 facilitators. The information is posted on paper and electronically and also distributed in mailboxes in the Science Learning Center. Except for the graduate student, the program is strictly on a volunteer basis. About 15–20% of the students in the Structure and Reactivity courses have participated in the semi-structured groups. The student leaders feel there is value in staying connected to the course material. The match-making service attaches an intellectual aspect to an important socialization goal for students in a large university environment: finding other students who want to work together in their study of chemistry. When appropriate, as in selection of one’s learning style and environment, we prefer to educate and provide choices from a menu of options rather than to force everyone into a one-size-fits-all program.

I. From the second week of the first-term *Structure and Reactivity* course:

(1) Draw 4 anions with the formula C_4H_7; 2 with resonance forms possible and 2 without (all atoms closed shell).

(2) Draw 4 cations with the formula C_4H_7; 2 with resonance forms possible and 2 without (all atoms closed shell).

(3) Identify the problems in the course pack of previous examinations that deal with the topics of resonance, formal charges, and Lewis structures. Do them.

II. From the fifth week of the second-term *Structure and Reactivity* course:

(1) Create 3 different $C_8H_{14}O_3$ ß-keto-esters, each with 2 active methylene protons.

(2) Create 9 electrophiles to use in combination with the nucleophile derived from each of the ß-keto-esters in part (1). Three of the electrophiles should be appropriate for an aldol condensation, three for conjugate addition reactions, and three for double alkylation reactions.

(3) What products are predicted for the hydrolysis-decarboxylation reactions of your 9 reaction products from part (2)?

(4) Find 3 examples of enol/ate chemistry in recent chemistry journals (note: this is how we create your exams!)

Figure 2. Sample tasks for semistructured study groups.

Students often know that study groups are a good idea but lack the experience to go beyond sitting at a table wondering how to structure the situation. The semi-structured aspect of these groups gives them options for the kinds of tasks they might undertake and provides resource support for the group leaders. A set of weekly tasks is posted in a public area. The tasks are open-ended, with the possibility for many different correct answers. Figure 2 shows such a set of tasks. Much like the assignments in a drawing class (“draw shoes”) or theater class (“depict anger”), the group has a common task that is open enough for individual creativity. This brings focus to the study groups and avoids many problems associated with them when they become freewheeling sessions that stray from the learning agenda, or when they form according to social, not educational agendas.

Our experience with the semi-structured study groups has evolved into a structured study group format of peer-facilitated sessions that now comprises the honors option for Structure and Reactivity students. A cohort of 120 first-year undergraduate honors students, while taking standard course work and examinations, earn honors credit by participating in extra weekly 2-hour sessions shaped along the lines of a performance studio in the arts. These sessions, which have a separate curriculum, are facilitated by seven upper-level undergraduates supervised by a faculty member teaching the course. The structured study group format answers the accountability issue that arises when evaluating the performance of honors students relative to their non-honors peers. The program has had a positive impact on students in the course, and even more so on the development of the facilitators’ leadership and teaching skills (*16*).

You have assigned a student the task of creating some multiplication problems, and these examples are presented:

2 x 2 = 4	-1 x 0.5 = -0.5	1.1 x 11 = 12.1
3.5 x 1.4 = 4.9	2 x 4 = 6	3 x 0.75 = -2.25

What advice do you give?

Figure 3. Exercise for demonstrating the importance of adopting the learner's perspective.

Drawing from a Full Menu of Socratic Instruction Strategies

Teaching with Trust

When training undergraduate study-group leaders or teaching assistants, we emphasize that finding ways to help students understand the basis of their errors is more helpful than simply deciding how incorrect they are. After one student gave an interesting series of Brønsted acids when prompted to list proton donors (she suggested HCl, then HI, then NaOH…), we shifted our perspective to the student's point of view when analyzing similar responses. We use the exercise in Figure 3 (*14*) as part of various training sessions.

These examples demonstrate the importance of trusting that students tend to be internally consistent in their use of strategies, and that incorrect strategies can produce the same answers as correct ones some of the time. The student who listed the acids explained that "proton" refers to any positively charged partner in a substance. Without the NaOH example, we might have attributed her suggestions of HCl and HI to knowing what proton donors were just because they appear on our lists, also. The lesson from the multiplication problems, inspired by the previous example, points to why just checking for right and wrong answers may not be much help in revealing students' misunderstandings. The advice given by individuals reacting to Figure 3 usually involves identifying the single incorrect example ($2 \times 4 = 6$) and reinforcing the notion that 5 out of 6 were correct. From the student's perspective, this could be the worst advice to give. To suggest that one answer is wrong could add even more confusion to this student's actual misunderstanding: that "×" designates addition and not multiplication. We recommend that the best use students can make of faculty time is to present instructors with copies of written examples or discussion *created* by the students without using other reference materials. Students appreciate how their expertise in multiplication allows them to rapidly evaluate the creations of someone learning to do multiplication. By analogy, they begin to see how faculty with expertise in chemistry can rapidly evaluate a page full of examples even though they are being seen for the first time.

Answering the Question: Am I Being Understood?

Chemistry faculty are the most experienced learners of chemistry. They should draw on their experience and imagination to tie what needs to be learned in chemistry together with the many strategies for learning and with how to choose among options (*17*). Reflective practitioners (*18*, *19*) can step outside the simple presentation of factual material to provide a "behind the scenes" interpretation of what appears in a text, at a demonstration, or on chalkboard and computer screens.

One overriding question drives all classroom activities: Am I being understood? Many levels of Socratic instruction can be used to gauge the level of student understanding. For example, when students are learning how to integrate the details of a topic such as "acylation reactions" with other knowledge, we suggest that they take a sheet of paper and create new examples of what they think are acylation reactions, using words and pictures. Then they present these examples to instructors or peers for evaluation. Modifications of this technique work well in a lecture period whether there are 30 students or 300. After creating 5 examples, pairs or trios of students take a few minutes to select what appears to be their best one. The lecturer can use some of these as the basis for subsequent discussion. On another day, the papers might be collected and some of the suggested examples reformatted and returned as a worksheet, for the class to determine which ones are appropriate. With patience, practice, and the right examples, a "conversation" can be held with a group of 300. Students can learn how to think in their seats and how to reply spontaneously.

Problems of the Day

The Structure and Reactivity course starts by exploring the concept of "connectivity" of molecular architecture. We should remember that a great deal of chemistry was based solely on the valence concept for 40–60 years before the discovery of electrons! We designed our instruction to introduce new concepts on a "need to know" basis: to bring in a more sophisticated idea only after we can describe the insufficiency of the students' current understanding. It is not good instructional design to begin teaching chemistry with the Schrödinger equation if the problems that it resolves are not within the context of a learner's experience. Thus in introducing the idea of resonance structures, we are explicit about the idea that resonance theory resolves an inadequacy of simpler Lewis electron dot models. Experimental observations of equivalent C–O bond distances in the actual structures of carboxylate groups is necessary and sufficient to expand the structural theory beyond the Lewis model. These examples illustrate the multiple ways in which we think about data. We demonstrate that we cling to useful models even when there is no good theoretical basis for them (*20*).

For initial practice with molecular assembly, students have access not only to conventional textbook exercises (*21*) but also to problems presented in class as the "Problem of the Day". Figure 4 is a typical problem of the day for the beginning of the course. Because such problems have the advantage of not being answered in the answer book that accompanies the text, we begin to establish the idea that the processes by which students learn to solve problems and the practice they acquire in doing so are more valuable than "knowing the answer" when they take an examination.

(1) Start with two carbon atoms, one nitrogen atom, and one oxygen atom; and

(2) explore the structures that are possible that:

(a) have all closed shell atoms, and

(b) have no net charge.

To achieve this, you will also have to use hydrogen atoms, as needed.

(a) What is the minimum number of hydrogen atoms needed?

(b) What is the maximum number of hydrogen atoms you can use with the other atoms given above?

(c) What is the jump in number of hydrogen atoms as you go from one set of structures to the set with the next highest number of hydrogen atoms?

Figure 4. Problem of the Day.

Faculty Workshops

Students, especially good ones, are accustomed to knowing the answer. Faculty tend to reinforce that image, especially after a number of iterations of the same course, when all the commonly asked questions have been repeated many times. Our experience in the subject matter of our courses gets further away from the inexperience of our next class of students each year. One thing students need to see is what we do when we do not know the answer. We need to model, repeatedly, how we step back, inventory the whole problem, sort out relevant from irrelevant data, grope for the correct concept to apply, make stabs at various solutions, and discard unfruitful starts. This includes assessing and evaluating solutions under consideration. We must show that it is acceptable not to know an answer right away—that we are willing to be wrong sometimes, but we keep going until we get all the pieces to fit.

One occasion for students to observe us as problem-solvers is our optional weekly evening workshop. The only ground rule is that students may not say, “Please do problem 23b.” We explain that this is not a meaningful question. We ask them to learn to identify and articulate what it is about problem 23b that is troublesome and what general concept they *really* want to discuss so they can answer problem 23b for themselves. It is useful to write all such questions on the board so some general themes emerge and the discussion is not defined by one disconnected question after another. These are treated in the context of increasingly complex open-ended questions or problems that we explore with students in a freewheeling way, always open to further questions. This is the “case-study” method of the social sciences applied to problems in physical science (*22*). We are explicit about the steps we are taking in order to demonstrate the process of problem-solving.

Workbook Exercises

Many things we expect students to learn have multiple layers of embedded assumptions. Representing the connectivity changes associated with chemical reactions is one of the first encountered, and arguably among the most important. We have devised workbook exercises that ask students to analyze bonding changes before they are formally responsible for the chemical content of the transformations. We encourage them to develop active observational skills and to understand what is implied by the representations used in chemistry. Figure 5 is an example of a workbook exercise from the beginning of the course. It would require students to say things such as “This represents a carbon-bromine bond being broken. The pair of electrons from that bond have become the fourth pair of nonbonding electrons on the bromide ion. The nonbonding pair on the carbon atom of the cyanide ion is used to form the new carbon–carbon bond. The sodium ion is a spectator ion. It is associated with whatever ion has the negative charge in this equation.” The tasks the students have to perform are concrete; the changes are visible, but students have to develop the language of chemistry in order to describe them.

In most chemical reactions, molecules undergo changes in connectivity, that is, in the bonding of their atoms. Learning how to identify these changes rapidly is a skill you should master. There are not very many things to monitor in reactions that you are presented with: (1) bonds broken; (2) bonds formed; and (3) redistribution of bonding and non-bonding electrons.

While you are becoming comfortable with molecular structures, it is a good idea to move back and forth between complete Lewis structures and the common abbreviations that are used. You should continue to monitor and to test your ability to identify whether or not atoms in a molecule have closed shell or open shell configurations and whether they are charged or uncharged.

Exercise.

I. Restate the following observation in terms of the bonding changes involved.

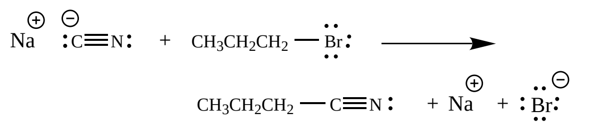

Figure 5. Workbook exercise in monitoring and representing connectivity changes in chemical reactions.

Collaborative Laboratory Tasks Promoting Cooperation (*23*)

We and our colleagues who teach general chemistry have designed our laboratory courses to reintegrate underlying liberal arts values, especially those related to organization and communication, along with the tactile operations of laboratory science. Our collaborative identification lab question “Who Has the Same Substance that I Have?” has also been a blueprint for other faculty to design activities in other disciplines (*24*).

Assessment and Evaluation Practices

Assessment and evaluation of student and faculty performance are inevitably linked. We teach the way we were taught and test the way we were tested, from student examinations to the superficial opinion polls called teaching evaluations. Since instituting our new program we have collaborated with colleagues in the School of Education and the Combined Program in Education and Psychology at the University of Michigan to explore and adapt assessment strategies that already exist in academe. Examples of student and faculty assessments that represent the kind of culture we are building in our department are (i) literature-based, case-study format examinations; (ii) examination of authentic skills by performance of an expert task; (iii) large-scale survey work and demographic analysis; and (iv) interview-based analysis and observation by experts outside the department. Survey and interview data are intrinsically neutral, and must take account of the entire culture of the course, the instructors, and the students. We are trying to demonstrate the value of combining a full array of complementary methods in order to learn about the teaching and learning practices in our courses.

Literature-based, Case Study-Format-Examinations

Examinations, probably more than anything else, transmit the learning agenda to students. Tobias refers to this attribute of examinations as the “latent curriculum” [to be published in Tobias, S.; Raphael, J. *In-Class Examinations in College-Level Science: New Theory, New Practice* (tentative title); California State University Press]. If examinations do not consistently and exclusively reflect goals, reform efforts are ignored by the learners for whom they are intended. We have selected examinations to begin this assessment section, rather than including them with the instructional strategies, because of our strong belief that examinations reveal at least as much about instructors as they do about students.

We recognized that organic chemistry was structured so that state-of-the-art information from the primary literature could be presented to novice students on examinations. This assures that we are true to the

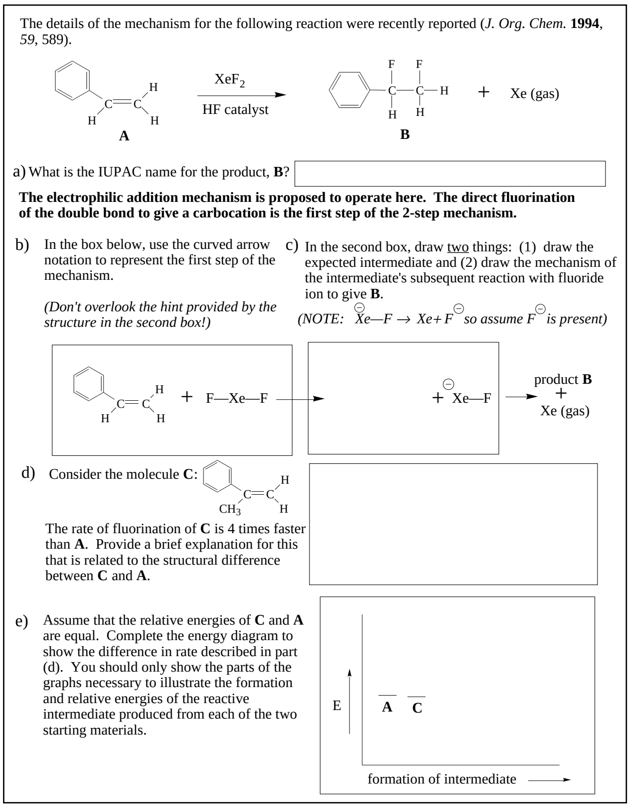

Figure 6. Sample examination question from the first-term Structure and Reactivity course.

facts of science and not simply inventing trivial derivatives of classroom examples. We include the citation along with some contextualizing statements, which sends two messages to our students: (i) memorizing the previous examples is not enough, and (ii) understanding the subject matter of the introductory course lets you understand some of what chemists actually say about what they study. The context of these problems has a great deal of intrinsic interest or relevancy because many examples come from medicinal and pharmaceutical chemistry or materials science. Our examination questions are like short case studies that can be explored by 1200 introductory chemistry students. Figure 6 is a typical question from the middle of the first-term course.

We reinforce the idea of multiple representations for the same phenomenon. Students might be asked to provide words, pictures, graphs, and numerical versions of the same idea. On nearly every exam, students suggest unanticipated but completely reasonable alternative solutions. These are important to note in class.

Two principles overlooked in most beginning courses influence our approach to undergraduate education and appear in the context of examinations: to be honest about the origins, operations, and limitations of science and to consistently show the assumptions, connections, and implications in representations used to describe the aspect of the natural world known as chemistry. Nelson (*25*) describes these as willingness to give students the rules of the game so they can play, too. These are not the usual lessons of introductory chemistry, where "content obsession" (*26*) is nowhere more strongly perceived than in traditional sophomore organic chemistry courses.

Grading in Laboratory Courses

Our grading system is based on evaluation of attendance, preparation, safety, and participation as well as the recording and manipulation of laboratory data. We provide periodic feedback as the courses proceed. Although most students are at first uncomfortable with the unstructured nature of these courses, within a few weeks anxiety subsides and a cooperative environment develops in the laboratory as students develop expertise at different rates. In discussions of research ethics in the formal education of scientists (*27–30*), one of the points we have raised is that responsible laboratory design should not promote or positively reinforce unethical behavior (spiking or stealing products, fabricating data, and so on). Not only have we tried to remove the incentives for unethical laboratory practices, but, by using the collaborative design described earlier, we have created a positive environment for ethical practice.

Performance-Based Assessment to Examine Laboratory Skills

In 1989–1990 and 1990–1991, classes of 400 and 600 first-year students, respectively, participated in the initial offerings of Structure and Reactivity. To gauge the effectiveness of our approach, we collected data on how the skills of a group of Structure and Reactivity students from the first two classes compared with those of two comparable groups from the traditional sophomore organic laboratory course. During the three-year phase-in of the new program and phase-out of the old, both groups were in our department in independent, parallel tracks.

Design and Analysis

To evaluate skill development, we used responses to an interview about an approach to solving a laboratory task. We interviewed three groups who knew nothing of the study beforehand. The first comprised randomly selected first-year students from the Structure and Reactivity course (11 each year), interviewed during the last few weeks of class. The second comprised randomly selected students from the traditional organic chemistry laboratory course (10 each year) interviewed during the same week. Although these students had had two full years of chemistry, they were the only legitimate comparison group because of their experience in organic chemistry. The third group comprised 2 upper-level graduate students and 3 faculty members, all organic chemists. We compared the two groups of student responses with the "expert" responses. Analysis based on use of concept maps has precedent and suited our purpose (*31*, *32*). The concept map compiled from responses of the experts to the solution of the laboratory problem (Fig. 7) was the basis for the comparison.

During the interview the student and the interviewer (BPC) sat alone together. Subjects were instructed not to reveal any information about the interviews to other students until all interviews were completed. A capped vial containing about 5 mL of a clear, colorless liquid (dichloromethane) was placed next to a tape recorder in the interview room. The subject was asked a version of the query "What stepwise procedure would you use to determine the nature of the material in this vial?" The interviewer challenged the responses in this "think-aloud" format (*33*) by questioning the significance of the suggestion ("What will you learn?") and submitting that the suggestion led to a new problem, asking how it might be resolved or reconciled ("That didn't work, what next?").

A feature of the concept map put together from the responses of the experts (Fig. 7) is the sequence of four main components of an ordered process: analysis, separation, purification, and identification (hereafter referred to as the four "general concepts"). Appended to these are the more specific concepts and practices. There are a total of 47 entries on the experts' concept map. Interviews from the students were transcribed and used to identify which components of the expert concept map were present in the statements made by students. A representative student map from each of the comparison groups is shown as Figures 8 and 9. Three features from the student interviews were noted. First, using a copy of the expert map as a template, the map entry was marked off when the student described the same feature. Second, the chronological sequence of the general concepts used to describe the process, as suggested by the student, was noted on the template. Third, when students suggested ideas not found on the expert map, these were mapped onto the template and counted separately.

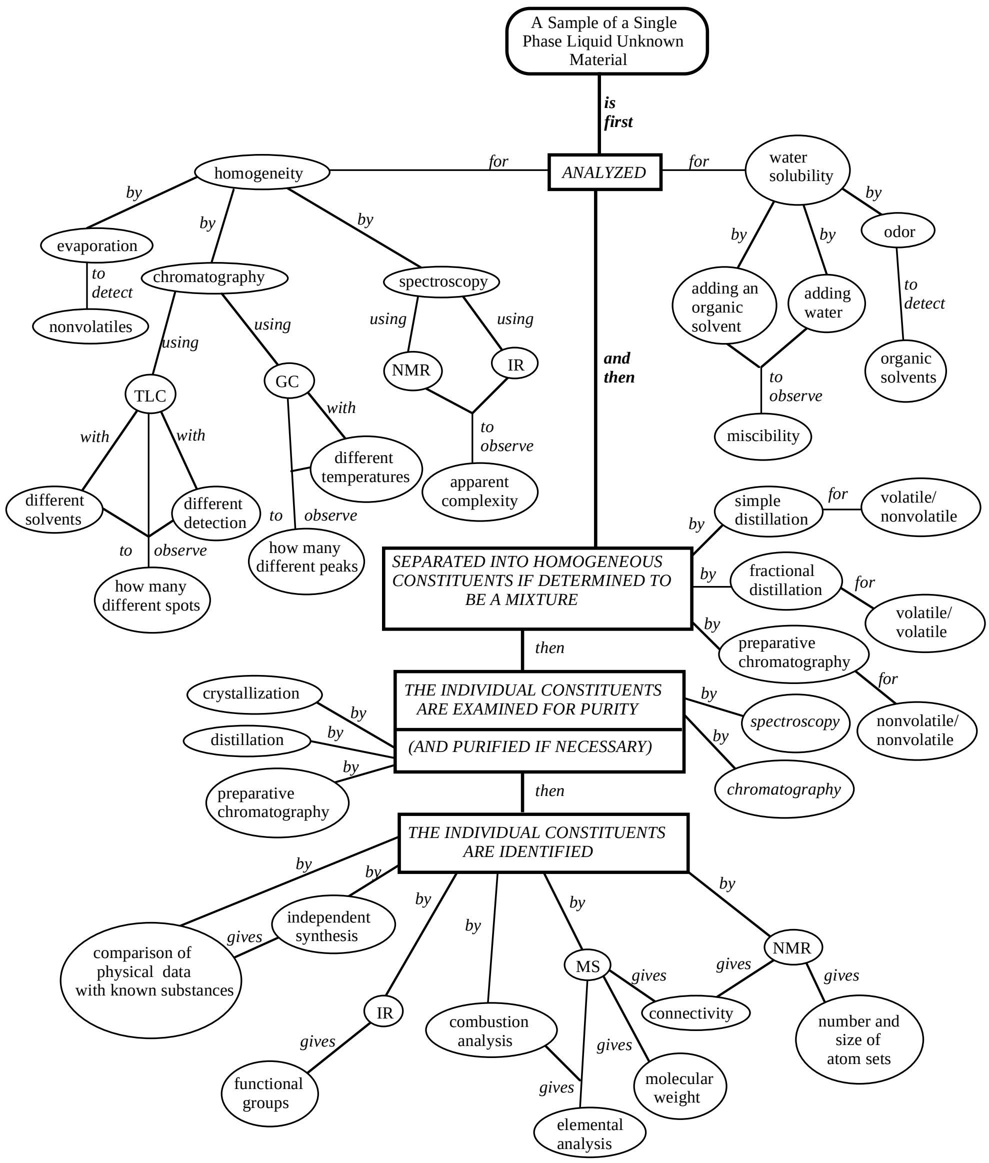

Figure 7. Concept map compiled from responses of experts.

Results and Discussion

One way to express the development of skills is the progression from novice to expert (*34*, *35*). Although true expertise is an amalgam of skills, appropriate and highly integrated knowledge and experience, and knowledge of what skills and information are needed in a given situation, students in the new first-year course appear to hold a more "expert" conception of the assigned task than students from the traditional course.

1. Nearly all of the Structure and Reactivity students (20/22) used 3 or 4 of the 4 general concepts, and 17 used the expert procedural order. Students from the traditional course focused on the identification aspect of the task. When they used an analysis step, they all used water solubility as structural evidence; *not one of these students explicitly considered the homogeneity of the sample* (left-hand branch on analysis concept). On the other hand, the 20 Structure and Reactivity students who considered an analysis step included analysis of homogeneity as part of their suggested solution.
2. The number of expert items matched by Structure and Reactivity students was nearly three times greater than that matched by students in the traditional course: 16.1 ± 3.2 vs. 5.9 ± 3.4 in 1990, and 13.5 ± 4.3 vs. 4.7 ± 2.4 in 1991. The experts (including the course instructor) provided 17, 20, 25, and 29 entries.
3. One experiment in the traditional course was the identification of an unknown aldehyde or ketone by chemical tests and preparation of a solid derivative. The additional items suggested by 12 of 19 students revolved around this theme. Structure and Reactivity students have routine access to FTIR, GC, and FTNMR data, and they reflect their comfort with the instrumental techniques by suggesting this kind of analysis as their primary strategy.
4. Structure and Reactivity students indicated a more intimate association with a laboratory environment and greater confidence in their own ability (*36, 37*; Enerson, D.; presented at University of Chicago Institute, Nov. 1988). At some point in most of the interviews, the idea arose of how one would identify a substance if it had not been characterized before and tabulated reference data did not exist.

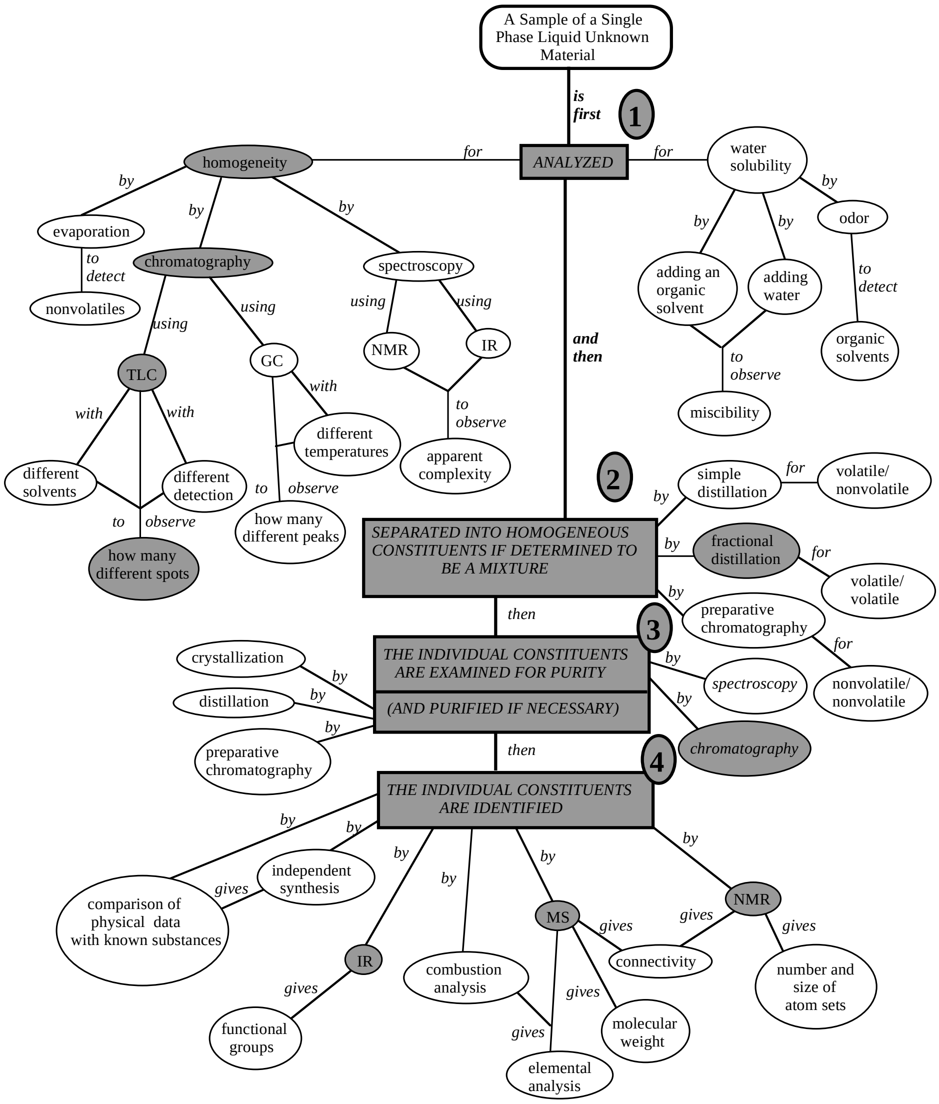

Figure 8. Concept map analysis for a student from Structure and Reactivity. Shaded areas represent items coded from the student's interview using a blank copy of the expert's map (Fig. 7; nothing outside of the expert's map was suggested). The main items (shaded, 1–4) were also suggested in the same order as by the expert.

The following responses are representative of Structure and Reactivity students:

- *I would think, from spectral data, I should be able to narrow it down to 2, maybe 1 structure.*
- *Get an IR, MS, NMR...then it shouldn't be too hard.*
- *...microboiling point definitely wouldn't help you. Do ^{1}H and ^{13}C NMR...certainly you should be able to determine the connectivity to some extent.*

Responses from the students in the traditional course:

- *We were never really faced with an "unknown", really, we were just following step-by-step procedures in the book, and I guess I'm kind of lost.*
- *...take a boiling point and see if there's a depression.*
- *[we were] doing experiments by following procedures in the book...not really thinking about what we're doing and why.*
- *Am I supposed to be able to answer this [question about the laboratory task]?.. they tell you everything in lab so you don't have to figure it out; you feel rushed and I don't even have time to ask why am I doing this?*

Large-Scale Survey Work and Demographic Analysis

Guided by experience and simple demographic analysis (average exam scores vs. attributes such as Advanced Placement, SAT, or ACT level, gender, ethnicity), we noted that many traditional predictors for academic success did not hold for students in Structure and Reactivity courses (Coppola, B. P.; presented at the 65th Annual Meeting of the National Association for Research in Science Teaching, Boston, MA; 21–25 March 1992). From interviews with students, it appeared that individual motivational issues coupled with examination practices played an important role in success (*38*). To examine this more rigorously, we collaborated with Paul Pintrich, director of the University of Michigan Combined Program in Education and Psychology. He has published a well-tested survey instrument, the Motivated Strategies for Learning Questionnaire (MSLQ) (*39*), a self-report 7-point Likert-scaled instrument (1 = not at all true of me to 7 = very true of me) to measure motivational beliefs and use of learning strategies.

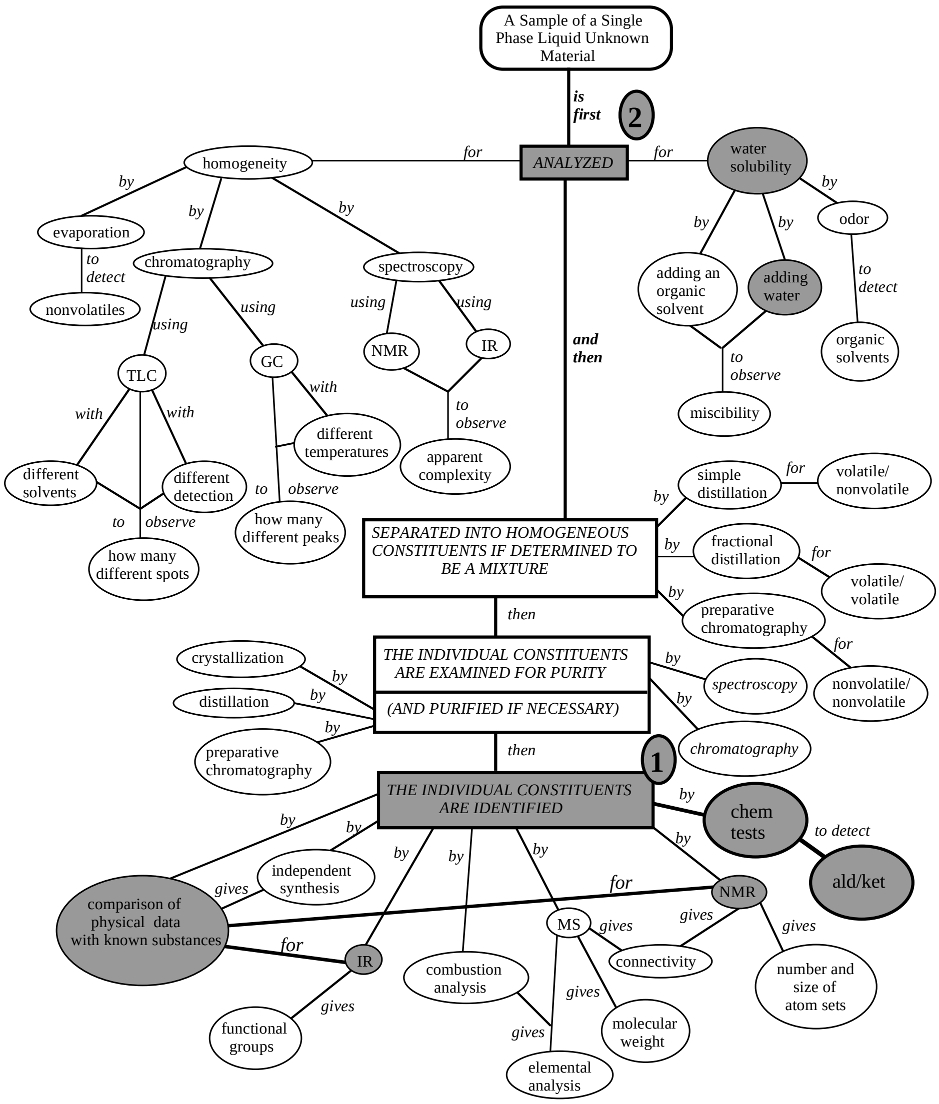

Figure 9. Concept map analysis for a student from the traditional 2nd-year course. Shaded areas represent items coded from the student's interview using a blank copy of the expert's map (Fig. 7; 3 items outside of the expert's map were suggested). A smaller number of main items (shaded 1 and 2) were suggested by the traditional student than by the Structure and Reactivity student, and they were suggested in a different order from that of the expert.

Design and Analysis

On the first and last days of class in the fall term, 1992, students in the first term of Structure and Reactivity and General Chemistry were invited to participate in the study. Data from the 1194 students who completed both pretest and posttest measures were analyzed; 516 students were enrolled in Structure and Reactivity and 678 in General Chemistry. Students completed a modified version of the MSLQ. To orient students to their beliefs and behaviors in chemistry class, the questionnaire asked them to respond in terms of their experience in the course in which they were enrolled. Four motivation scales and three learning strategies scales were used. In our 99-item questionnaire, each category (scale) is represented by 4–9 questions that ask students to reflect on specific studying and learning behaviors. A brief description of each scale is provided below (*39*).

Intrinsic Goal Orientation is the degree to which the student feels he/she is participating in a task because of challenge, curiosity, or mastery as an end in itself.

Task Value is the student's evaluation of how interesting, important, and useful the course material is.

Self-Efficacy is composed of self-appraisals of one's ability to master a task and confidence in one's skills to perform that task.

Test Anxiety involves a student's negative thoughts that disrupt performance on exams, and an emotionality component concerning affective and physiological arousal aspects of anxiety.

Surface Strategies are basic rehearsal strategies such as reciting or naming items from a list to be learned. Best used for simple tasks and activating information in working memory rather than acquiring new information in long-term memory, Surface Strategies do not seem to help students construct internal connections among pieces of information or integrate new information with prior knowledge.

Deep Strategies include elaboration and organization strategies. Elaboration strategies include paraphrasing, summarizing, creating analogies, and generative note-taking. These help the student store information into long-term memory by building internal connections between items to be learned and connecting this information with prior knowledge. Organization strategies involve clustering and selecting the main ideas from reading passages and notes; these help the learner select appropriate information to be learned and build connections between this material.

Self-Regulation refers to the processes of controlling cognition via planning, monitoring, and regulating activities. This scale deals with monitoring activities such as tracking one's attention while reading, self-testing, and questioning.

Pretest measures were used to control for preexisting differences in the two groups of students. Preexisting differences were controlled for statistically by use of analysis of covariance (ANCOVA). In all ANCOVAs we tested the assumption of homogeneity of regression coefficients in order to meet the assumptions of ANCOVA, and this assumption was met in all analyses.

Results

General Chemistry students' scores on the MSLQ at the end of the term (posttest) were compared with Structure and Reactivity students' MSLQ posttest scores. The ANCOVA adjusted the posttest means according to any pretest differences between the groups. Table 1 shows the adjusted mean scores for each course on the posttest scales. As shown in the Motivation scales listed in Table 1, Structure and Reactivity students ended the semester with significantly higher Task Value than did students in Chemistry 130. Similarly, Structure and Reactivity students were higher in Intrinsic Goal Orientation. However, in contrast to hypotheses based on other studies, where increases in these two motivational scales also result in greater belief in one's ability to turn effort into outcome (*40–45*), students in General Chemistry reported greater levels of Self-Efficacy at the end of the term than did Structure and Reactivity students. Concomitantly, students in Structure and Reactivity expressed significantly higher levels of test anxiety than did their General Chemistry peers.

With respect to learning strategies, there was no difference in Surface Strategies used by students in the two courses. However, in line with our greatest expectation, Structure and Reactivity students did report significantly greater use of Deep Strategies than students in General Chemistry. Finally, Structure and Reactivity students indicated significantly more use of Self-Regulatory strategies than did the General Chemistry students.

Table 1. ANCOVA Means on Posttest MSLQ Scales Adjusted for Differences in Pretest

Variables	Adjusted Means				F value[a]
	Chem 130		Chem 210		
	X	S E	X	S E	
Motivation					
Task Value	5.04	0.04	5.29	0.05	16.28**
Intrinsic Orientation	5.15	0.03	5.34	0.04	12.51**
Self-Efficacy	5.07	0.04	4.90	0.05	6.06*
Test Anxiety	3.53	0.05	3.87	0.05	23.18**
Learning Strategies					
Surface Strategies	4.47	0.05	4.54	0.05	0.98
Deep Strategies	4.64	0.03	4.94	0.04	32.70**
Self-Regulation	4.68	0.03	4.85	0.03	18.26**

[a]Statistical significance is denoted as follows: * $p < .05$; ** $p < .001$.

Discussion

A bimodal distinction is not expected for the comparison of students in these courses. The nature of large-scale survey work aimed at psychological and cognitive attributes reveals trajectories within large populations and movement in the center of mass. Discussions and leading references about the use of quantitative measures in chemical education research can be found in a series of articles in this *Journal* (*46–48*).

Statistically significant results are often easy to identify when comparing large populations, so it is important to look at the interaction between multiple scales within the context of overall course design. The simplest interpretation of the MSLQ results is also the most satisfying: examination practices are important in transmitting expectations, for both faculty and students. The higher levels of Task Value, Intrinsic Orientation, Deep Processing Strategies, and Self-Regulation are all positive reflections on the Structure and Reactivity instructional environment. The fact that Structure and Reactivity students were lower in Self-Efficacy and higher in Test Anxiety than General Chemistry students is consistent with the great difference between examination methods used in Structure and Reactivity and the more familiar and comfortable multiple choice or algebra-based word problems used in high school and General Chemistry. Because of these results, the faculty in the Structure and Reactivity course have adopted a practice, used by General Chemistry instructors, of providing a more elaborate examination practice package along with specific written suggestions for study practices.

Finally, the similar levels of Surface Strategies demonstrated by the two groups of students confirms the ubiquitous nature of these strategies. Many tasks require rote memorization of information, and students routinely use rehearsal strategies as a means of memorizing material. Indeed, the fact that the Structure and Reactivity students reported comparable levels of Surface Strategies as did their General Chemistry peers, despite receiving exam questions that emphasized more elaborate synthesis and required pictorial and written answers beyond rote report of material, points to something we have often stressed: although we are interested in promoting the development of higher-order skills, we want to do this elaboratively. Experts rely on memorized information coupled with their analytical skills; the critical expertise is knowing what to use when.

Large-scale survey work is one way to take snapshots of student populations. These pictures do not exist in a vacuum, but need to be informed by views such as the other assessments described in this section. We have duplicated this study and are performing the complementary analysis of our data, which is to correlate pretest and posttest results with student achievement. All this work is motivated by the idea that it will provide us with better advice for students at the beginning of the courses as well as a diagnosis of factors that correlate with academic success.

Interview-Based Analysis and Observation by Experts Outside of the Department

Another way we have obtained information about our instruction is to invite education scientists and psychologists to interview faculty and students on questions of common interest. The simplest version of this strategy is to invite colleagues interested in science education to observe and comment. Therefore we have opened our classrooms to our colleagues and invited their written commentary. In an extended visit, a graduate student in chemical didactics from the University of Nijmegen held a term-long internship in Ann Arbor. He participated as a graduate assistant in the recitation and laboratory of Structure and Reactivity and as an expert observer and interviewer of the instructor and students. His report was the basis for oral and written presentations from his chemical didactics study (*3, 49, 50*).

Goal Matching

We were interested in the match between the instructional goals articulated by faculty in a course and those held and perceived by students. In the Structure and Reactivity courses in particular, we encourage faculty to think beyond the details of chemistry content, and with our students to move beyond the objective of simply getting a grade. In a series of interviews, faculty from our traditional General Chemistry course were asked to identify their instructional goals. Joseph Krajcik, a faculty member in our School of Education who specializes in chemistry instruction, conducted the interviews with the faculty; James Hovick, a lecturer in our department who had taught in both Structure and Reactivity and General Chemistry, conducted the student interviews (*51*). In every case, the replies from the faculty in the General Chemistry course were one version or another of "subject matter mastery". Goals from the faculty interviews included: *Balance equations; redox chemistry; periodicity; special lectures on environmental and materials chemistry; polymers; problem-solving; doing calculations; atomic structure; do demonstrations to bring ideas together; mixing "spit back" questions with ones that ask students to "synthesize".* Students in the same course, after it was completed, were queried about their goals. Interestingly, none of them tied "getting a good grade" to any other, more general skills: *I didn't have any goal, but I wanted an A; I got an A by memorizing equations and doing exam problems that were exactly like the problems I had seen on previous tests...I don't know what goals my instructor had...as far as I am concerned I did not need to go to class.*

We proposed to resolve these conflicts in goals by bringing "cognitive process instruction" to the core—by teaching in a way that accounts for how students learn (*52*). Learning skills and strategies become common outcomes for faculty and students engaged collaboratively in learning about learning the subject matter. Faculty in Structure and Reactivity were interviewed also. From the faculty (none of whom are the authors): *Students get to do things for themselves; become comfortable with uncomfortable ideas; become independent learners, understand how scientists think by using our particular discipline; apply concepts to novel situations and feel comfortable; make connections about what and how very explicit; open a new intellectual horizon.* And from the students: *To get an A and along with that comes an understanding of what's going on. I equate good grades with understanding, that idea's been drilled into my head.*

Small Group Instructional Diagnosis (SGID)

Since 1990, the Center for Research on Learning and Teaching (CRLT) at the University of Michigan has offered the opportunity for SGID visits to a number of large introductory courses on our campus. Small Group Instructional Diagnosis (*53, 54*) involves an independent staff of facilitators (CRLT staff) who canvass the entire set of recitation or laboratory sections for a course in order to hold 20- to 30-minute focus group sessions. The SGID staff supervisor meets with the faculty in charge of the course to customize the agenda for the midsemester group discussions. Facilitators guide each group of students to a consensus on what is going well and what is not going well in the class. The information is compiled, patterns are identified, and feedback on the graduate student teaching assistants and senior instructor(s) is then discussed in confidence with the graduate students faculty for the purpose of improving teaching.

Laboratory Design

During one of the early offerings of the second-term laboratory course, we again invited Krajcik to spend an afternoon with our laboratory students during an actual laboratory session. Krajcik's written commentary on what he observed is significant:

> My conversation with the students also revealed they believe it is important to justify and explain the procedures they performed rather than arrive at a "correct" answer. None of the students felt they had to find the "right answer," but rather needed to explain why the procedure was performed.
>
> From a science education perspective, students were involved in designing experiments, testing out designs, evaluating, redesigning, and retesting. From my conversations with the students, their experience in the laboratory course resulted in applying their knowledge of organic chemistry in a problem-solving environment.
>
> Organic chemistry laboratory for these students was not a process of verifying facts but a process of applying and constructing knowledge. These are important objectives for students in a laboratory course. From my brief interactions with students in this course, it appears that students achieve these objectives.

Between the skills-based task performance evaluation and Krajcik's observations, we conclude that the abilities demonstrated by the Structure and Reactivity students do indeed reflect a more "expert" conception than those of traditionally trained students. We attribute the difference to the laboratory environment (especially the integration of hands-on instrumentation) and to the underlying difference in course design and philosophy. An important anecdote from the first class of Structure and Reactivity students indicates that we are able to leave students with a more expert view of the processes of science in general. In their sophomore year, these students encountered their first laboratory course in introductory physical and analytical chemistry. In order to create a "puzzle", the faculty had modified a laboratory experiment where, traditionally, all students measure the vapor pressure of samples of a single organic substance. In the new version of the lab, each student was given an unidentified organic solvent and was asked to identify it by comparing the measured vapor pressure with a set of tabulated values. For another group of students, this might have added an adequate level of mystery to the lab. Instead, these students analyzed the identification problems they were given and then devised and implemented a solution: they obtained NMR spectra!

Summary

We have made progress in our view of instruction by taking a more explicit perspective on our goals. In restructuring our classroom practice, we identified five principles that have guided our instructional design and helped students develop their higher order skills.

- Give out the implicit rules.
- Use Socratic instruction.

- Create alternative metaphors for learning.
- Use authentic problems to elicit authentic skills.
- Make examinations reflect your goals.

Course content and methods of instruction convey messages about philosophy and values whether or not the instructor consciously subscribes to such a philosophy and value system. It has been as important to be aware of the changes that were needed (or that had already occurred) in ourselves as to think about changing our instruction. The design principles listed above are outcomes of and inextricably linked to our underlying philosophy.

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