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In the Classroom

Progress in Practice: Three Plenaries I

Richard N. Zare, Enhance, Enable, and Elucidate

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A discipline is more than its facts; a discipline also includes the way in which one operates on those facts to create meaning (understanding).

On May 10–11, 1997, the Day 2-to-40 Conference was held at the University of Michigan. The proceedings from this meeting were reported in a special issue of *The Chemical Educator* [**1998**, *3*(1)]. Three plenary sessions were held for the conference participants, featuring talks from distinguished chemists who are respected for their viewpoints on the connections between chemistry, chemical education, the rest of the academy and society in general. The first of these talks was given by Richard N. Zare, Marguerite Blake Wilbur Professor of Natural Science in the Department of Chemistry at Stanford

Individuals involved in curriculum design often introduce new, modified, or applied ideas about instruction that span from classroom methods to philosophies of education. In this series, we examine progress in chemical education that is related to actual practices, and where many recommendations have originated from areas in higher education that exist alongside of and overlap with chemistry. Rather than an exhaustive review, we will select examples, background, and vocabulary that may either invite interested newcomers to explore a different area in their teaching, or provide language and precedent for individuals who wish to contextualize ideas they have developed independently.

—Brian P. Coppola, Series Editor

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University and Chair of the National Science Board. This article is a report on the talk given by Professor Zare. Quotations are based on a videotape recording of his talk. The transcript has been edited for clarity and continuity.

The Responsibility of the Teacher

During his session, Zare reported on some of the underlying philosophies that influence his behavior as a faculty member in the classroom. He first reflected on the tension between his roles as a deliverer of different kinds of subject matter content: chemical facts, chemical science, the broader aspects of scientific practice including the place of science in society. Zare began,

> We have all been to these kinds of meetings before and we hear the speakers say that the real problem is that students simply need to know topics A, B, and C or they cannot learn D.… Chemistry is presented as the series of topics that comprise a syllabus...so the meetings commonly address two problems. First, we hear how to teach topics A, B, and C. Second, and too often, what we end up hearing is how students have not ended up with A, B, and C from the prior course, even when it was that faculty member's responsibility to have taught it!
>
> I think that the real role of a teacher is to motivate students to learn a topic. Inspiration is more important than information. We underestimate the ability of students to learn. When it becomes clear to students that we expect them to learn, and when we provide them with some guidance for learning this subject of ours, then students can learn when they want to. The instructor must serve as an enabler of student learning but not necessarily the prime provider of information.

Zare's first point cannot be overemphasized. As advances in molecular science have caused a true information explosion across many disciplines aligned with chemistry, there has been an increased tendency to focus chemistry instruction on what I have called the "professional technical goals," in other words, the factual subject matter [1]. Yet, as chemists, we are the most qualified group to demonstrate how our subject is connected to the broader lessons in chemistry ("professional intellectual goals") as well as to the general educational value in learning the subject ("general intellectual goals"). All of these things are validly viewed as the subject matter of chemistry. After all, regardless of how deeply one understands bricks, concrete, wood, windows and shingles, these objects do not imply the construction of a building.

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Zare then moved to a related topic: the medium versus the message. If the materials used to make a building do not imply their use, it is equally difficult to infer any of the rules for creating a portrait in oils by studying the tubes of paint and the blank canvas. A discipline is more than its facts; a discipline also includes the way in which one operates on those facts to create meaning (understanding). The need to "perform" ("operate on the information") is perhaps more obvious in some disciplines, such as art or theater, compared with chemistry, regardless of our use of the word "performance" in describing student work. In these other areas teachers must explicitly include how one operates on the material objects used by the discipline as a natural part of designing instruction. Perhaps musicians have an advantage over chemists: the difference between music and its representation on a sheet of paper is quite clear.

> Books are good. [Zare began his commentary on media with this simple declaration.] Books are better than most people for conveying information.

Zare's point can be restated more broadly: the medium is only the carrier of the message, and the message-maker controls the outcome. Every medium has its own set of strengths and weaknesses for conveying meaning. Understanding the idiosyncratic power of a medium is the first step to effective communication through it. Zare continued,

> I believe we are going to gain from high bandwidth and high computer power. Multimedia is an important aspect of this, for sure, but multimedia is not an end as much as a means. We all know that there are multimedia evangelists (multimedia bigots, perhaps) who say that people will be replaced in the process of converting to multimedia instruction. I disagree. When I look ahead, I see that the teacher is still involved, and not just for creating the lessons. The learning process relies on contact. There has to be a human contact for motivation and communication. We barely know how people learn, really, except that interpersonal interactions are at the core of the process.
>
> Computer logic will improve, and when you look at, the objective is to emulate the characteristics that sit at the core of one-on-one contact: customized correction, on the fly, while speaking out loud (explaining). The goals for these new technologies, it seems to me, should be to enhance, enable, and elucidate. These are the same goals in all interactions between a teacher and a student.

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Returning to one of his original themes, Zare said,

> Human motivation still comes from interpersonal interaction. Once you have gotten to the point where people want to learn (and assisted in this process), then lots of different tools can come through to assist this.
>
> Just the other day I was asked by two members of Congress about knowledge and distributed intelligence. The question was specifically related to the use of the World Wide Web in teaching. I told them the same thing I am telling you: it is up to teachers to set the tone for getting the receiver (and creator) of knowledge ready to receive (and create) that knowledge.

The Craft of the Teacher

Zare turned his discussion to the decisions made by instructors in designing learning environments for their students.

> I want to start with the traditional lecture course. Some students learn well this way, others do not. I think we should think in terms of multiple modalities rather than single modes. Looking back, lectures did not motivate me the most for my interest in science. It was the hands-on experiences: first in my basement, then in my courses, and finally in the research internships I held. Lab courses can play a key role in motivating interest and understanding in science, but the experience has to be more than teaching lab techniques!
>
> Getting back to my own courses for a minute, let me review what I mean by multiple modalities. I give homework that is graded. Even if I am not the one who looks at it every time, someone has to look at it. If I do not think enough about it to have it be a graded part of the course, then why should my students do it? I also have students work in study groups, sometimes to solve new problems and other times to go over the work they have already done. I use an electronic bulletin board for exchanges of information. I participate in the discussion, but I try not to dominate it. Previous students from the course participate also. This exchange of questions makes the course go outside the classroom. I also take my classes on tours of local industry, an easy thing to do in the Silicon Valley but something that might be more difficult elsewhere. My students return from these trips with new eyes about the world. I hold evening discussion sessions, sometimes the students come to me and sometimes I go to the students in their residence halls.

The Obligations of the Chemistry Teacher

> Chemistry is the central science. At a recent American Chemical Society dinner for Chemical and Engineering News, the hosts wanted to get comments

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from some of us on what we thought chemistry would look like 35 years from now. In my after-dinner remarks, I suggested that 35 years from now chemistry might not be around! That certainly got everybody's attention. I explained that I was not predicting the disappearance of the chemical sciences, but rather the loss of the core, a switch from the creators of chemistry to the users of chemistry, because we (creators) will have given up our ownership. The chemist is becoming the “modifier”-chemist; that is, the “biochemist,” the “materials chemist,” and so on.

Chemistry instructors work with lots of service users of chemistry, including many premedical students. The number of actual and even potential majors in the introductory program is small. That is okay. I am not as interested in creating hundreds of new majors as much as I am in having students understand why chemistry is interesting.

At Stanford, we decided to create three versions of our introductory chemistry course depending on the science and mathematics backgrounds of our entering students. Each fall, the entering class at Stanford has around 1500 students, and we see about 800–900 of them in chemistry. I should say that I am not going to describe a model for a program that I am trying to sell. Nothing is exportable, really, because we all live in unique departments within unique institutions. I hope you might be able to use what I say to make analogies. Now I will get back to the courses. About 175 of the first-year chemistry students come to us with Advanced Placement in chemistry, some come in with less preparation. When we gave one course to everyone, it was one big group running in the marathon of the introductory course. The experienced marathon runners finished just fine but were bored; the inexperienced (even disabled) runners finished last, of course, and were turned off; and some the ones in the middle ultimately finished after a lot of sweating. Why hold this race when you know how it is going to turn out before it starts? We now divide the class into three sections, all taught by the senior faculty. This last part might surprise you. At Stanford, we do not hire people who do not want to teach, and we do not promote people who teach badly and who might be better off if they belonged in a research institute.

We believe in getting our students to organic chemistry early. The connection of organic chemistry to biological sciences and other interesting things makes this subject a compelling topic for students to experience. My course, called Chem 32, is for prepared students who are also prospective science and engineering majors. These students have AP Chemistry exam scores of 4 or 5, so we accept that they have seen enough general chemistry and we move on. As I said before, it is not my goal for all of these students to choose chemistry as a career, but rather to be truly educated in chemistry.

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Chem 32 is a team taught course which I have been doing with Jim Collman. This team-up works well. I am a destructive chemist, I tear apart molecules; Collman is a constructive chemist, he is interested in building them up. We have pledged to each other to be at class all the time, and to start debates on some topics, which is not difficult to do precisely because we come with different viewpoints.

We offer an integrated laboratory course with Chem 32 where we try to extend the interconnections we are after in the lecture course into the experimental setting. We begin the course with the topic of molecular symmetry. Interestingly, we always lose some students at the beginning because the course is not a repetition of their high school chemistry. They do not know yet that they need to cope with subjects and ideas they have not seen yet! Symmetry leads to discussions of chirality, polarity, dipole moments, and to molecular structure and some simple organic chemistry. It is a short walk from there to spectroscopy and the interaction of light with matter. We then move to coordination chemistry and to separation science. We combine traditional polymer chemistry, which is certainly industrially relevant, with bio-polymers. We end with the physical chemistry of these topics (thermostatics, thermodynamics, kinetics) and with molecular solutions to medical therapies. Our goal is to get these students excited. The inventory of topics may not look like the traditional course, but they really do learn a great deal of chemistry through the context of how we do science.

In the lab course we spend practically the entire term exploring the chemistry of a single substance. We start with the synthesis of a ruthenium bipyridyl compound done in water. We prepare it, purify it, and record all the usual spectroscopic information (NMR, IR, UV, MS). After we have characterized the compounds, we then examine their chemistry. We look at the fluorescence of ruthenium compounds while bubbling oxygen, nitrogen, and then air. This gives us three points for Stern-Volmer kinetics done on the quenching of the fluorescence. We get a chance to observe this in real time. We also study the oxidation-reduction chemistry. We use chemistry as a tool, and we make no particular point to segregate the subdisciplines. These students do not exit saying “I am a ‘fill-in-the-blank’ chemist.” Our goal here is unity and exposure across all domains.

Four Last Thoughts for the Bigger Picture of Higher Education

Before I finish, I want to spend a minute or two with some larger issues about education in general. The first is a problem with our institutions exemplified by a few failed efforts to teach a chemistry course for nonmajors. I taught this for a few years, but only about 30 students ever took the course. The university did not commit to helping the course grow; it was simply deemed noneconomical. I think these students are not getting what they need from

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> their education. Indeed, I do not think that "educated people" are being graduated if they leave the university as academically disadvantaged, perhaps even crippled, because they do not have an appropriate study of math and science. This is especially true for people who go into public service and need to make decisions about scientific and technological issues. Why did this program for nonmajors suffer so? I do not know. Perhaps a course based on organic chemistry would have been better so that we could teach from a more biological context.
>
> Another problem is in multidisciplinary instruction: who owns what and who gets credit for it. The structure of the university simultaneously enhances and inhibits the things we want to do. There are parts of modern chemistry that overlap substantially with modern biology, and there should be a deep articulation between them, yet the ownership question is the fundamental paradox of multidisciplinary programs (this affects the NSF, too, by the way). Departments exist to give like-minded scholars a common home. These same departmental divisions also create interfaces and intersections. If you set up an interdisciplinary program and it is not owned by a single unit, it will generally fail.
>
> A third topic is grading policies. In Chem 32, we have enough experience to grade on an absolute basis. We explain this to the class as best as we can, and we use this as a way to urge students to work together. Whatever can be done to minimize the destructive effects from competition is good. This kind of competition creates a poison for learning in the traditional class because it removes students from serving as resources for each other. We want them to work together in order to learn. Grading on an absolute scale, and taking the time to explain things, is terribly important.
>
> Finally, I want to say a few words about graduate teaching. My course in advanced quantum mechanics is difficult; it is hard for the students and it is hard for me, too. In addition to simply giving problems, I wanted to inspire some ownership for the students. Instead of a final exam, I asked the students to use a part of the class notes as a starting point for a research project. I asked them to pick an area of interest within their class notes and to fill in the blanks, to flesh out the notes they took in class and turn them into a really good outline of the topic. They would start with their own set of notes, then go to the library and amplify the topic by filling into the gaps behind the information I brought to class. My goal is for my students to get something out of this for themselves.

Many of the ideas Professor Zare described in his presentation are good examples of what we mean by creating a student-centered approach to learning. The effect on Zare was equally clear in his closing lines:

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Teaching chemistry is a blast. I get a boost from all perspectives.

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