

REPRINTED FROM

LIBERAL *AAC&U* EDUCATION

VOL. 82, NO. 4

FALL 1996

TEACHING CHEMISTRY AS A LIBERAL ART

DUDLEY HERSCHBACH

ASSOCIATION OF AMERICAN COLLEGES AND UNIVERSITIES

DUDLEY HERSCHBACH

TEACHING CHEMISTRY AS A LIBERAL ART

FOR THE PAST FIFTEEN YEARS I have taught general chemistry in various versions to large classes of up to 350 students, chiefly freshmen.

It has been a challenging and satisfying

experience. Students have nicknamed this course "Chem Zen." Perhaps naively, I like to think that endorses its key underlying theme: *science as a liberal art*. Although the course includes plenty of technical material, my approach emphasizes the human adventure, replete with foibles as well as feats, in exploring a fabulous molecular world.

As in the course, I will try to convey aspects of this "liberal science" theme by means of some whimsical metaphors, deriving from two questions addressed to the class: How many of you admire impressionistic paintings? How many have studied a foreign language? I also describe specific efforts to implement the theme in the major components of the course: lectures, homework problems, lab, and exams. I conclude with a plea pertaining to science literacy.

Impressionistic epistemology

A liberal education aims above all to instill the habit of self-generated questioning and thinking. This habit is essential for science, but too often it is not fostered in introductory courses. Any chemist can attest to the usual reaction on

being introduced to someone at a social occasion. Almost always they turn pale or wince, then refer to a mystifying college or high school course. My reaction is sympathetic, since I recall my puzzlement when I first met chemistry as a high school junior; only after many weeks did I begin to "get the hang of it." Now I think the root problem, confusing for students and teachers alike, resides not in the quirks or atoms and molecules, but simply in how we think and talk about them.

My favorite way to explain this to my students invokes a metaphor: *Chemistry is like an impressionistic painting*. If we view it from too close, all we see is bewildering detail in myriad dabs of paint. If we look from too far away, all we see is a shimmering blur. At the right distance, wondrous and lovely things appear.

The metaphor emphasizes that, of necessity, chemical descriptions and concepts call on a wide variety of levels of abstraction or approximation. These differ markedly in rigor or sophistication. Until the neophyte develops the knack of picking up clues that specify the appropriate level, most everything will be out-of-focus. Even professional scientists often have the same trouble with chemistry. Physicists always want to reduce things to first principles; they tend to stand too close. Biologists usually want to resolve only the broad features; they tend to stand too far back. Either way, the chemical ideas disappear. There is much more to the painting than the paint.

The focusing problem actually often be-

My approach emphasizes the human adventure, replete with foibles as well as feats, in exploring a fabulous molecular world

DUDLEY HERSCHBACH is Baird Professor of Science at Harvard University. He was awarded the Nobel Prize in chemistry in 1986.



Dudley
Herschbach
demonstrates
how to
make nylon

comes kaleidoscopic. Discussion of a typical chemical topic may invoke in quick succession concepts (e.g., reaction rates, thermodynamics, molecular geometry, electronic structure) that pertain to quite different levels of abstraction. Yet students can and do become very adept at kaleidoscopic focusing, and with less effort when made aware that it is needed. Moreover, they soon recognize that the same kind of alertness for context and referents is intrinsic to the study of humanities and social sciences. Chem-

istry, like other liberal arts, obliges us to look for the painting rather than the paint.

Anyone who learns to read or speak a foreign language—including science, mathematics, or music—is empowered by gaining access to exhilarating new cultural domains

Empowerment by language

Another apt metaphor depicts science as a language. In introductory science textbooks, the number of new or ordinary words used with special meaning is comparable to the vocabulary of a typical language text. Likewise, the array of interlocking concepts met in a science course functions much like grammatical rules. I tell my students about a study

conducted by Richard Light, based on interviews with eight hundred Harvard seniors or freshly minted alumni. When asked what academic class they felt had been most valuable, most said it was a language course. Anyone who learns to read or speak a foreign language—including science, mathematics, or music—is empowered by gaining access to exhilarating new cultural domains. This metaphor is useful in advising students how to approach the study of science.

An aspect emphasized by a language metaphor is the kinship of neophyte students with research scientists. Nature speaks to us in many tongues. They are all alien. In frontier research, the scientist is trying to discover something of the grammar and vocabulary of at least one of these dialects. To the extent the scientist succeeds, we gain the ability to decipher many messages that Nature has left for us, blithely or coyly. No matter how much effort we might devote to solve a practical problem in science or technology, failure is inevitable unless we can read the answers that Nature is willing to give us. That is why basic research is an essential and practical invest-

ment, and why its most important yield is ideas and understanding.

In delivering this sermonette, I like to add that the beginning student and the veteran research scientist are very much alike in an important respect: Much of the time both are quite confused! That makes many students uneasy or even distraught. However, puzzlement is welcomed by the scientist, who realizes it's usually prerequisite for any exciting new insight. The veteran researcher is also aware

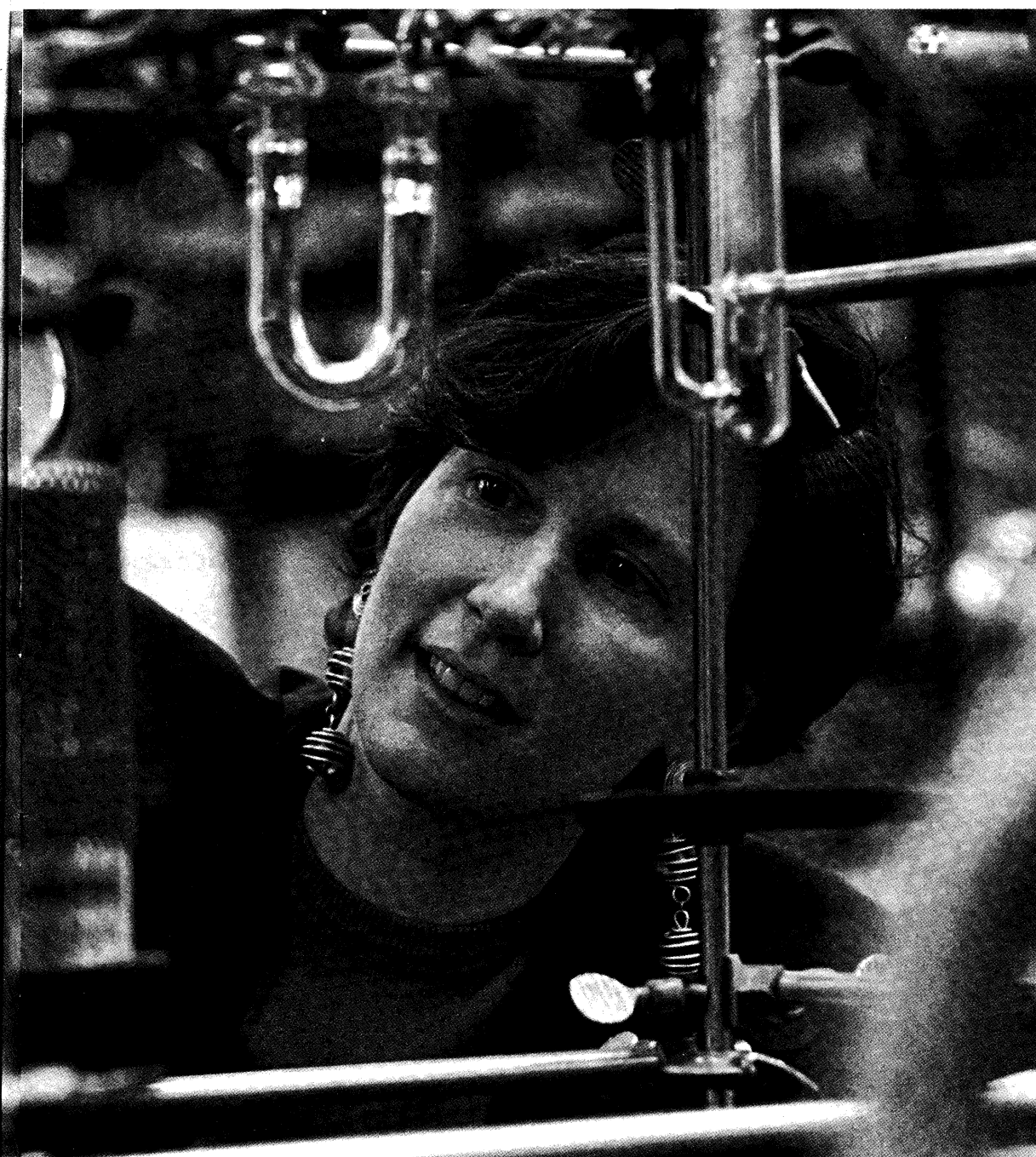


of a tremendous advantage enjoyed by science: The goal, call it truth or understanding, waits patiently to be discovered. That is why marvelous advances can be achieved by ordinary human talent, given sustained effort and freedom in the pursuit.

The class is always startled when I ask how many students can read Braille or sign language. We are all born blind and deaf to Nature's language, and it takes much persistent groping and guessing to learn something of it. Ironically,

typical science courses, unlike humanities, inhibit the willingness of students to guess. I try to counteract that with questions that cannot be approached otherwise. Of course, a genuine expert is also obliged to devise means to test the guesses. Like a child trying out new words, a scientist eagerly tries to converse with Nature. Students need to do that, too. They should be encouraged to become actively engaged, and, despite inevitable linguistic confusion, to persevere with sangfroid.

**Chemistry
professor
Cynthia
Friend,
Harvard
University**



Parables and paradigms

Most students taking freshman chemistry have already had a high school course. Thus, they have encountered many standard topics, such as the gas laws, acids and bases, covalent bonding, etc. However, rarely do students have any notion of how such prototypical concepts emerged, how widely applicable they are, or how they affected other developments. In view of this, in my lectures I now introduce each major topic with a story, usually having the character of a parable. By presenting science in a more humanistic mode, these parables can disarm fears, reveal a much broader context for nominally familiar concepts, and even induce students to relate the tales to others.

Many of the parables deal with historical episodes or current research discoveries; some are fanciful. Often the stories emphasize the role of analogy and guesswork or show how error and failure are prevalent in science but can foster progress if "wrong in an interesting way."

The introductory story for my lecture on gas laws is titled "How Aristotle and Galileo Were Stumped by the Water Pump." After illustrating how such a suction pump works, because few students have seen one nowadays, I note that Aristotle "explained" it by his famous dictum that "Nature abhors a vacuum." Then I raise the question why the pump will not lift water above a height of thirty-four feet. This empirical fact was known in Aristotle's day, as evident from artwork that depicts a series of pumps lifting water from a deep river gorge, with human figures providing the scale. Curiously, Aristotle said nothing about why a tall drink seems to quench Nature's abhorrence. Two thousand years later, Galileo specifically considered that question. He suggested that the pump ceases to function because a taller column of water would break of its own weight. That answer is also quite wrong; when asked for contrary examples, students quickly point to waterfalls and fire hoses.

The right idea was proposed by Torricelli, one of Galileo's students. (I enjoy pointing out that some of today's students are likewise destined to solve problems that have long stumped their professors.) Galileo knew that air had weight and had devised a means of weighing it, but he did not connect this with the operation of a water pump. Torricelli realized that the weight of the air would force water to rise in the pump barrel. This concept implied that the

observed limit of thirty-four feet represented the weight of water that the pressure of the air on the earth's surface could maintain.

To test his idea, Torricelli tried an experiment. For convenience, he used mercury, a liquid about fourteen times heavier than water. If he was right, the atmospheric pressure should support a column of mercury only about one-fourteenth as high as that of water, or about thirty inches. His apparatus was simply a glass tube about three feet long, with one end sealed. He filled it with mercury, then inverted the tube in a bowl of mercury open to the atmosphere. In repeating this experiment for my classes, I'm always elated to see the mercury column in the tube drop to a height of about thirty inches above the level in the bowl. From weather reports, everyone knows about variations in atmospheric pressure, but few are aware that it is still monitored by Torricelli's barometer, in essentially the same form he devised 350 years ago. I go on to demonstrate how vacuum pumps, evolved from the barometer, enabled measurements that established the gas laws.

The story offers several morals. It illustrates well how a maverick idea, tested by experiment, can overthrow long-accepted doctrines. The vacuum left between the top of the mercury column and the sealed end of the glass tube refuted Aristotle's dictum. His venerable authority did not yield quietly. Many scholarly papers in Torricelli's day tried in vain to save the old view by postulating such things as invisible threads holding up the mercury. The story also shows how a new conceptual paradigm gives rise to experimental techniques that further extend its scope. Above all, it exemplifies how profound insights may lurk in seemingly mundane observations.

Another favorite tale introduces my lecture on polymer chemistry. This is titled "How Nylons Won World War II." In 1927, the DuPont Chemical Company set up a laboratory to study polymer chemistry. This was regarded as foolish by several serious chemists of the day, who were still arguing whether polymers were really macromolecules or just gunk at the bottom of a flask. To head the new laboratory, DuPont brought in Wallace Carothers. As a young assistant professor at Harvard, he had already become obsessed with the idea of synthesizing artificial silk. Within a few years Carothers and his colleagues, building on his academic research, had succeeded in making

**Profound insights
may lurk in
seemingly mundane
observations**

several important polymers, including nylon. However, much longer was required to produce a marketable fabric. DuPont steadfastly supported this work for thirteen years before it had anything to sell, a commitment unprecedented in American business at that time. (Would it be possible today?) The return on this investment has been immense. Over fifty years since this entirely synthetic fiber was first marketed, the annual worldwide production of nylon has reached about ten billion pounds. Made from four of the most common elements—carbon, hydrogen, nitrogen, and oxygen—this silklike stuff and kindred polymers fulfill the ancient alchemical quest to produce gold from dross.

Today, the bountiful harvest from polymer chemistry and its garbage is evident everywhere. However, because mention of science is largely excluded from our history books, most citizens know nothing about many instructive episodes, such as the crucial role polymer synthesis had in World War II. The infamous Japanese attack on Pearl Harbor in December 1941 was much less crippling than the fall of Singapore three months later. That deprived the United States and its allies of virtually their sole supply of rubber, a vital commodity. A report to President Roosevelt put the case starkly: "Of all the critical and strategic materials, rubber presents the greatest threat to safety of our nation and the success of the Allied cause.... If we fail to secure quickly a large new rubber supply, our war effort and our domestic economy both will collapse." This report launched a crash program to produce synthetic rubber, using a method developed and implemented in Germany. In effect, our enemy had mapped the route to salvation. All told, some fifty plants were quickly built; some are still in operation today. The Allied victory could not have been achieved without this enormous rubber project. But for it to succeed on such an urgent timescale, we had to have a sufficient population of polymer chemists and engineers. It was the pursuit of artificial silk started fifteen years before and culminating in nylon that largely created those vital human resources.

Poetry for chemists

An introductory science course too often comes across to students as a frozen body of dogma. The questions and problems seem to have only

one right answer, to be found by some canonical procedure. The student who does not easily grasp the "right" way, or finds it uncongenial, is likely

to become alienated. There seems to be very little scope for a personal, innovative experience. Nothing could be further from what actual frontier science is like. At the outset, nobody knows the "right" answer, often not even the right question or approach. So the focus is on asking an interesting question or casting the familiar in a new light.

Concern about this syndrome led me years ago to ask my students, at two or three points in the term, to write poems about major themes or concepts: wave-particle duality, entropy, or a host of others. That is more like doing real science than the usual textbook exercises. In fact, I find that most students have never tried to write a poem before and have no idea how to go about it. That, too, is like real science, where we grope along, run into dead ends, try again, and slowly find a way. A selection of the class poems, judged best by the teaching fellows and me, is posted in the science center library. Also, I award the authors a charming little book of verse by Robert W. Wood, a pioneer molecular spectroscopist, also celebrated for his practical jokes. In 1917 he published a book entitled *How To Tell the Birds from the Flowers*, a collection of fifty woodcuts, each illustrating a poem. Here is a stanza from one of my favorite poems by a student, Kerry Bron, titled *Quantumland*:

Do you know a special secret place
Filling much of invisible space
Where frogs can only jump so far
And the range of an ordinary bike or car
Can be only ten or twenty miles
And every person has only half or whole smiles
Where dogs bark at specific levels of pitch
And people can only be a certain amount rich?

I also show the students many poems that pertain to science, intentionally or not.

Qualitative problem solving

Introductory courses in physical science typically put much emphasis on solving numerical problems. Students certainly need to develop competence and confidence in solving such problems. But just as with other skillful arts, like music, dance, and sports, practice rou-

Students
working in
Harvard
University
Science
Center
laboratories



tines do not automatically produce happy results. Exercises overdone or poorly done often induce dullness or bad habits. The usual textbook problems should bear a warning label: *Too much exposure to this stuff is dangerous to your mental health!* Typically, the danger is manifested in three ways:

1. *The plug-and-chug syndrome.* Many students seek to minimize exposure. This is done by flipping rapidly through the textbook to find formulas in which to insert the data supplied in the problem. Authors and editors take great pains to make this process easy, but that is not always obvious to a hasty, drowsy student.

2. *The just-the-right-data syndrome.* Almost never does a patient tell a physician exactly, nothing less and nothing more, what the doctor needs to know for a diagnosis. Yet, by long-established custom, that is what is done in textbook problems. This deprives the student of the opportunity to practice two key aspects of any genuine problem solving: *asking* "What do I need to know?" and *discerning* what is significant information.

3. *The don't-know-how syndrome.* Studies in cognitive science show that even quite able students cannot solve problems only slightly different from those they have done before, *unless* they have a qualitative understanding. The usual textbook problems condition students to rely on a carefully structured context, to follow a safe path to the right answer. Guessing and qualitative reasoning is thereby discouraged. Students too often do not discover how much they can figure out on their own, the most gratifying and essential lesson.

The four preceding paragraphs are from my introduction to a book of problems prepared by Dan Brouch, an excellent head teaching fellow for Chem Zen. The book presents one hundred *qualitative* problems, spanning the whole subject matter of the course. None requires other than trivial arithmetic. Each has a plausible "real-life" or humorous setting. Some even have more than one correct answer. At least one has as yet no known correct answer, but the wrong ones are nonetheless instructive, as often happens in scientific research. By avoiding the usual syndromes, the book aims to help students nurture latent talent for qualitative reasoning. This is needed as well to handle any numerical problems of the honest kind, so-called word problems that require understanding to set up calculations.

Safari in the chem lab

Too often, laboratory work in general chemistry courses has a ritualistic character. Students follow a carefully specified protocol, enshrined in a laboratory manual and interpreted or reinforced by priestlike figures garbed in white coats—the teaching fellows. This fosters slavish imitation and timidity rather than the self-reliant, innovative, *experimental* spirit that is the *essence* of science. The approach taken in Chem Zen simply emulates the pursuit of actual frontier research in order to encourage students to be adventurous and enterprising.

**A liberal arts
education must
aim to integrate
science into our
general culture**

Nothing is done as an exercise for its own sake; rather, everything serves as preparation for projects *chosen by and designed by* the students.

The lab manual, titled *Chemistry Safari*, was prepared in several successive editions by Paul Ma, another excellent head teaching fellow. The manual offers a user-friendly guide, rather than itemizing a step-by-step path. The journey is enlivened and aided by the company of Jafari, an evangelical and exuberant commentator strikingly like Paul Ma. During the early weeks of the term, students read general descriptions of six to eight feasible projects in a "Chosen Adventure" section at the back of the manual. Literature references allow them to track down pertinent background. Each student selects a general project and starts developing a personal version. In each of the first seven weeks, students carry out a training project acquainting them with basic techniques in a different area of chemistry. These require working out designs in a "Jungle Bootcamp" portion of the manual. The last four weeks of the term are devoted to executing the chosen adventure. A report in the style and format of a research article is required. It is submitted, reviewed by teaching fellows, and accepted, rejected, or returned for revision and resubmission in the same way articles are handled by science journals. In recent years, several of the best reports have been published in a *Journal of Undergraduate Sciences* launched by Paul Ma and alumni of Chem Zen.

Exams and grades

Student attitudes and morale naturally are greatly influenced by exam and grading policies. Chem Zen has two distinctive precepts: (1) no competition among students is allowed and (2) no points can be "lost" on hour exams.

To implement the first, we simply use an absolute grading scale, defining at the outset how many points from exams, homework, and labs are needed to reach each grade level. This enables us to encourage students to help each other and to assign some homework and quizzes as team problems, again emulating how most real science is done. In principle, everyone can get an A, in contrast to the customary, mindless grading on the curve, which guarantees disappointing a fair fraction of the class.

I call the second a "resurrection" policy. Any

points a student fails to earn on an hour exam are added to the corresponding section of that student's final exam, so the student gets a second shot at earning those points. This reduces

anxiety about a subpar performance on an hour exam and helps students to view the exams as trial runs indicating what to focus on most diligently in preparing for the final. By extension, this policy also offers a paradigm for later life.

Science literacy

A liberal arts education must aim to integrate science into our general culture. Many admirable efforts have been made, but at present science literacy, by any sensible definition, remains remarkably low even among college graduates. It seems to me unlikely that much will be accomplished if we continue to confine science to separate courses. Even a "physics for poets" course reinforces the prevalent view that science belongs solely to its professionals.

My experience with Chem Zen, reinforced by conversations with many students who have avoided science, convinces me that it would be feasible and worthwhile to include scientific parables in many other subjects: history, economics, even literature. This is affirmed by students in such fields, not in my course, who attend lectures or come to my office hours in order to pursue a parable they have heard about. I urge science teachers to become unabashedly evangelical by suggesting suitable parables to receptive faculty colleagues. For instance, the Harvard core course on East Asian civilizations, nicknamed "Rice Paddies" by students, should say why these cultures rely on rice rather than wheat, a striking science story with links to much else. Liberal science can foster an educational alchemy that seeks to make the whole greatly exceed the sum of its parts. □

REFERENCES

- Conant, James B. 1947. *On understanding science*. New Haven: Yale University Press.
Cromer, Alan. 1993. *Uncommon sense: The heretical nature of science*. New York: Oxford University Press.
Holton, Gerald. 1986. *The advancement of science, and its burdens: The Jefferson lecture and other essays*. New York: Cambridge University Press.
Shamos, Morris. 1995. *The myth of scientific literacy*. New Brunswick, N.J.: Rutgers University Press.