Teach to Search

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George Pimentel was a wonderful man, whose heart and soul were in chemistry. And just as much in research, in which he excelled, as in teaching. From his writing it is clear that he did not separate the two. Nor do I, which is why I am happy and proud to be associated with an award given in George Pimentel's name, and especially one in chemical education.

I will speak of two themes:

- The inseparability of teaching and research. And for that matter, of chemistry and the world.
- The necessity of chemists to teach broadly, to speak to the general public. And the tensions that arise in the process.

But before I launch into these subjects, let me say some words about how I feel about teaching and receiving this award. Whatever success I have had I owe to teaching. The logic or rhetoric of teaching underlies my research within chemistry and my writing outside of chemistry. As I began to think about this, I felt suddenly a little less guilty about receiving an award in chemical education.

Let me tell you why I felt—feel—guilty. What am *I*—viewed by the community of chemistry as a researcher whose work has received ample recognition—doing getting an award that should be given to those who have toiled so hard, dedicating their lives to chemical education? When there aren't too many of these awards around….

A second source of guilt for me is that I suspect that a significant component in the thinking of the Pimentel award committee was my role in making the Annenberg/CPB television course in chemistry, *The World of Chemistry*. I *was* a member of the team, indeed, and my soul and sweat went into the project. But the part I played—more than just being a pretty face, true—was in fact much smaller than the parts of several other people, who really deserve recognition.

I will tell you about those people in time. I do feel guilty about receiving this award, but my guilt is assuaged just a little by pride in the fact that I have not only taught thousands, but I have also taught others to teach. I have taught, subtly, the research community in chemistry that teaching strategies are productive in research. And I have contributed, I think, to the growing respect for teaching in the community of chemistry at large.

I

First let me address the issue of teaching and research. A damaging misconception about modern universities is that research dominates and diminishes teaching, and that the tension of balancing (unsymmetrically) the twain is unhealthy. Defenders of the universities argue that the two functions are complementary and that research or scholarship enhances the quality of teaching. I go further: I say research and teaching are, quite literally, inseparable. And they are symbiotic.

One root of the error, I believe, lies in thinking of learning in terms of place rather than audience. Places (classrooms, labs, library carrels) are, indeed, circumscribed, but the audiences of learning (undergraduates, graduate students, faculty, our minds) always shift, overlap, and enrich each other, like the colored glass bits of a kaleidoscope.

As I reflect on the possibility of a separation of research and teaching, I look at my research group. We meet twice a week—four graduate students, four postdoctoral associates, and I. One time we talk about the incredible, fertile literature of chemistry, while in the other session one of the people in the group reports on work in progress. We also ask why marzipan pigs are popular in Denmark, explain all those football and baseball metaphors in colloquial English to our foreign group members, and try to guess who is likely to be the author of those scurrilous referee's comments on our last paper. In these group meetings half the time I'm giving a monologue; the rest of the time the hardly shy remainder of this research family speaks. Is that research, is that teaching?

I go further: I say research and teaching are, quite literally, inseparable. And they are symbiotic.

I travel to the University of British Columbia to lecture about my work—about making and breaking bonds in the solid state. Ninety percent of the audience consists of graduate students, with a sprinkling of undergraduates. I talk to *them*. Is that research, is that teaching? I think the answer in both cases is yes. It's research and it's teaching.

Teaching and research are inseparable. The struggle to do both well enriches our personal intellectual lives, and enhances our contributions to society.

I am certain that I have become a better researcher and a better theoretical chemist because I've had to teach undergraduates. When I began at Cornell, I thought I knew all about thermodynamics, all those beautiful partial differential equations that relate the derivative of

A with respect to *B* to *C*. But thermodynamics is a subject of great richness, with practical common-sense roots (steam engines, the boring of cannon) and a mathematical structure of breathtaking sophistication. I had followed only the latter and hadn't really understood the full empirical beauty of "thermo" until...I had to explain the subject to students *without* the crutch of the mathematical apparatus. The more I taught beginning classes, the more important it became to me to explain. The rhetoric of pedagogy permeated my research. I think those in the community of chemistry who know my work will recognize what I mean.

I think there is nothing unique to me in all this. I believe that rather than treating research and teaching as disparate activities, it is more productive to cast the discussion in terms of *audiences* for creative work in science or the humanities.

In the beginning is research or discovery, a gleam of the truth, or of a connection, within an individual's mind. Actually I've experienced such moments, and so have others, most often not in isolation but in discourse with another person. Or when I sit down to write a paper, before me the draft or progress report by one of my students.

In fact, understanding already formed in the inner dialogue between parts of me, me and an imagined ideal audience of one, or of a multitude, in the lonely dialogue with the voices of skepticism and self-doubt that are all me, all of me.

Deep in
it's a docile crowd
most of the time, lazing
around, waiting for the train
of concentration to haul a few words
onto paper. It listens, then it stirs, the one
that speaks in many voices, to say:
these are just words, falling limp
into the untensed space they need sculpt, or:
make me understand.
They hate my compromises.
Here and there they offer up a phrase.
In their babble I hear the voices
of my teachers rise from a page or café. Sometimes
one speaks with an accent—I think
it's my father, it's him, the world
I have to please.
For them I leave no word unturned.
For it I sing, tone-deaf that I am,
the song that frees itself within.

In the next stage the audience expands to my research group. In the process of talking to them my understanding of the discovery deepens, takes a stronger hold on reality. Then I write a technical paper. Now my audience is out of my control. Writing is the message that abandons, as Jacques Derrida has called it. I can't grab that removed reader in Poznan or Puna and tell him no, you must read it this way and not that way. It has to be all there, in the words with which I struggle. It has to be there—the substance of what I found and the argument to convince him or her, the absent reader. I write for that audience from a position of substantive ignorance about them. I don't know their preparation, their level of sophistication, their willingness to work to reach enlightenment! It begins to sound an awful lot like teaching.

To me, the writing of a research paper is in no way an activity divorced from the process of discovery itself. I have inklings of ideas, half-baked stories, a hint that an observation is relevant. But almost never do I get to a satisfactory explanation until I have to, which is when I write a paper. Then things come together, or maybe I make them come together. F. L. Holmes has argued convincingly the same point, that scientific writing and scientific discovery are not disparate activities. In an analysis of draft manuscripts of a Lavoisier memoir on respiration he "...could watch important ideas emerging, growing, changing form or decaying during the evolution of a scientific paper."

An invited technical seminar introduces another audience. Sure, I want to impress my colleagues; claim precedence, power; please real or surrogate parents. Many things go on subliminally in the course of any talk. Yet most of all I want to impart real, significant, new knowledge. But the audience includes people of disparate backgrounds. The organic chemists may not know much about my present loves, which are surface and solid state chemistry. Depending on their background, different parts of the audience may attach different meanings to the plain English words at my disposal. There are many graduate students here. I want to teach all, convince all. Remarkably, incredibly, we can do it—speak to many audiences at the same time. That's what teaching is all about.

To me, the steps from a research seminar to teaching a graduate course, then an undergraduate one, are small moves in interacting with the continuous, over-

lapping spectrum of audiences. In the theater of the mind the audience is always shifting, never constant. There are different strategies (call them tricks, the stuff of experience), that one applies with audiences of young people that one might not try in a research group meeting. But the similarities of pedagogical strategy across the spectrum of teaching/research far exceed the differences.

The spiritual rewards for opening a person's mind, sharing new-found knowledge, are also quite similar. I've taught introductory chemistry many times, to thousands of students. There is the same unmitigated pleasure that hits me when I detect, on an examination or by the nonverbal signs students give in lectures, that someone has understood the magnificent and simple logic of the mole, so that he or she can tell me how much sulfur there is in a pound of sulfuric acid.

To return to my main point, I wish to argue that the desire to teach others, enhanced by being *obliged* to teach others, leads to greater creativity in research. The rhetorical imperative operates to make a scientist or scholar examine widely the potential responses (objections?) of his or her audience. Having to teach enlarges one's encounters with real audiences and therefore sharpens the imagined audience one engages in the inner dialogue in the course of research.

I do not mean to imply that you need to be a researcher to teach well, nor that you absolutely must teach to do research well. A reviewer of this paper appropriately reminded me that the "vast majority of high school and college teachers who contribute mightily to innovation in our field...are not researchers." I recall the tremendous success of the graduates of City College in New York (which 60 years ago had little research activity) and the many small colleges that are the baccalaureate source of our best researchers. And there are many talented researchers working in industry and government who have little occasion to teach. I respect the multiplicity of professional styles.

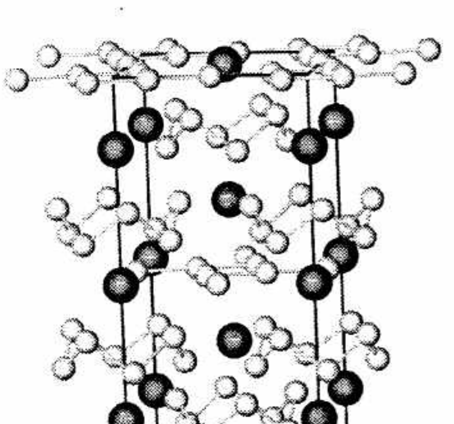

Figure 1. The structure of Cs_3Te_{22}. Small circles are Te atoms, the large gray circles are Cs atoms.

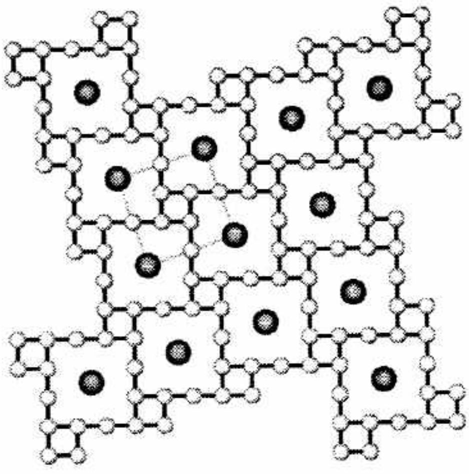

Figure 2. A top view of the $CsTe_6^{2-}$ net. One unit cell is highlighted by a square.

As my friend R. Freis has pointed out, following St. Thomas Aquinas, teaching is truly a cooperative art. It *works together* with the nature of the student as learner, knower, apprentice, in order to bring that nature to its perfection. Teaching is clearly also a rhetorical act. But it is more than mere persuasion because of its empathetic, reflexive aspect being cooperative. How could a mind that faces up to the problem of teaching a novice something new and difficult possibly avoid using the same strategies in explaining to itself something still more new, more difficult? Which is what people call research.

II

I want to try to illustrate to you what I mean by the rhetoric of teaching influencing my research style. To do that I've picked a recent paper entitled "A 2,3-Connected Tellurium Net and the Cs_3Te_{22} Phase", written by Qiang Liu, Norman Goldberg, and myself, to be published soon in *Chemistry, a European Journal*. Our work grew out of a paper we saw by Sheldrick and Wachhold in a February 1995 issue of *Angewandte Chemie* (W. S. Sheldrick, W. S.; Wachhold, M. *Angew. Chem. Int. Ed. Engl.* **1995,** *34,* 450), who reported a new Cs_3Te_{22} compound. Now the chemistry of tellurium is very rich. For instance, in the Cs–Te system some nine binary cesium telluride phases ($CsTe_4$, $CsTe_5$, Cs_2Te, Cs_2Te_2, Cs_2Te_3, Cs_2Te_5, Cs_3Te_2, Cs_5Te_3 and Cs_5Te_4) had been reported earlier, and two more have been made since.

The beautiful structure of the Sheldrick and Wachhold compound (Figure 1) displays a number of unusual features. Discrete crown Te_8 rings can be easily identified in Figure 1. Though such eight-membered crown-shaped molecules are well known for sulfur and selenium, they had not been previously observed for tellurium. Also apparent are infinite two-dimensional sheets that are formed by Te atoms and that include one Cs atom per six telluriums. Each Cs atom in the $CsTe_6$ sheet is located in the center of a large square of 12 Te atoms. The structure may also be described as consisting of two different types of layers: $CsTe_6$ sheets separated by layers of $CsTe_8$ crowns: $[CsTe_8]_2[CsTe_6]$. If one assumes the Te_8 rings to be neutral molecular entities and assigns the valence electrons of cesium fully to the only atoms left, the tellurium sheets, the compound may be described as $[Cs^+]_3[Te_8]_2[Te_6^{3-}]$. The Te_6^{3-} net is definitely electron-rich.

The pattern of the $CsTe_6$ sheet is remarkable (Figure 2, looking down the *c*-axis onto the sheet; the darker and larger spheres are Cs, the light ones Te). This is a rare net; the C_4 axis is the principal symmetry element present (aside from twofold rotation axes and the mirror plane containing the sheet itself).

...sure that such pedagogically driven paper-writing strategies are as disliked by some reviewers and some journal editors as they are appreciated by the young researchers who read these papers. Sometimes it has not been easy to get such teaching–research narratives published.

So far, you see an intriguing structure. That was apparent to the authors and readers of the initial report; they saw the same beautiful structure that I show you. Next we, as theoreticians, did the stuff of our trade, a calculation of the electronic structure of the three-dimensional material. The outcome is shown in Figure 3. It is a so-called band structure, showing the energy levels of the molecule.

Now if the pedagogical imperative were not important for me and my group, I think I would have (in an alternative universe, I can't imagine doing so here) stopped pretty much with an analysis of the bonding, perhaps worried about stability, and reached the conclusion that the material might be a conductor. But in my real world of trying to *understand* this big molecule, of trying to see its connection to everything else in the molecular world, that band structure is just the beginning. I look at that incredible net with fourfold symmetry, and I see in it two kinds of Te atoms. One is linear, bonded to two other Te atoms. Call this Te2. The other, which we call Te3, is T-shaped, bonded to three Te atoms. It is important to note here that the Te2 and Te3 notation does not refer to a crystallographic numbering; it is our way of reminding ourselves of the coordination environment of each Te.

I think about these; where else have I seen two- and three-coordinate tellurium or its analogues? Where else have I seen tellurium squares?

Well, for two-coordinated main-group EX_2 molecules, both bent (H_2O, H_2Se, H_2Te, and Te_3^{2-}) and linear configurations (XeF_2 and I_3^-) are possible. Why is Te2 linear in this sheet?

The T shape of Te3 reminds one of the BrF_3 molecule, and it does occur in a number of other extended tellurium structures.

As far as squares go, there aren't that many main group element squares around. E_4^{2+} species (E = S, Se, Te) are known, as is Bi_4^{2-}, and they are isoelectronic with electronically happy $C_4H_4^{2-}$. To my knowledge there are no square hypervalent molecular groupings with halogens, noble gases, or metals.

As we wrote this paper, I felt it essential to construct our understanding of the extended structure through molecular models and bonding schemes drawn from model molecules. Which is what we did. We began by looking at a simplified model for Te2 by calculating a Walsh diagram (i.e. how the energy levels of this triatom varied with bending at tellurium) for H_2Te^{n-}. We found (not surprisingly) that the preferred geometrical configuration of H_2Te^{n-} depends strongly on its electron count. The molecule prefers a bent geometry when it is neutral, as expected. And the triatomic H_2Te^{2-} is linear, analogous to a hypervalent H_2Xe or F_2Xe. We also looked at a more realistic model for the atomic environment of Te2 in the solid, Te_3^{n-}.

Next I will actually quote a piece of our paper (omitting references, of which there were many), not because it is important, but because it helps me make two points:

> A connection needs to be made here to the classical and well-characterized linear triiodide I_3^-. This species is, of course, isoelectronic to Te_3^{4-}, as is the related XeF_2. The bonding in I_3^- or XeF_2 is very well understood—we have in these molecules an electron-rich three-center bond. If one omits the *s* orbital on the central atom from the bonding, one expects the level pattern at left in [Figure 4], while if the *s* orbital is included we get the pattern at right. Note in either case that one and only one I–I–I antibonding orbital remains unfilled....

Why do I quote this? First, the subject just happens to be related to work that George Pimentel did. He and Rundle first explained qualitatively the bonding in triiodide anion and related electron-rich compounds. Second, I see this section as an example of the teaching imperative influencing research. In this section and in the

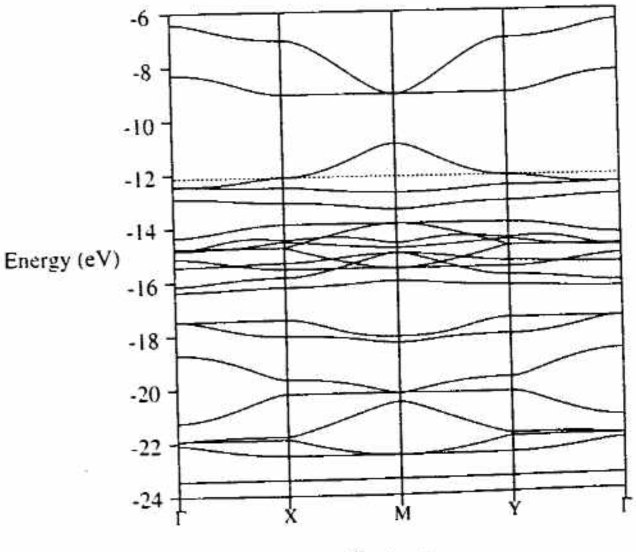

Figure 3. Band structure for the Te_6^{3-} sheet.

paper as a whole, I am intent on drawing the connection to electron-rich three-center bonding. And I will *not* assume that everyone has seen it. So I repeat an orbital level scheme—that's part of my teaching-in-research strategy—even if that level scheme has been in the literature before. I repeat it because that orbital scheme is part of the story; the story is incomplete without it; I am anxious to get into the mind of the poor graduate student assigned by his professor to talk about this paper at the next group meeting; I'm interested in teaching that graduate student, and—you know, it actually helps *me* understand this bonding if I explain it in detail, as if I were teaching....

Ignorance of chemistry poses a barrier to the democratic process. I believe deeply that "ordinary people" must be empowered to make decisions...

You can be sure that such pedagogically driven paper-writing strategies are as disliked by some reviewers and some journal editors as they are appreciated by the young researchers who read these papers. Sometimes it has not been easy to get such teaching–research narratives published. But I persevere and sneak them in. As here.

Let me show you another piece of this paper which makes some reviewers see red:

> The T shape reminds one of the BrF_3 molecule, whose bonding is described qualitatively in Figure 5. Note the formal F^- nature of the "axial" fluorines. We see two lone pairs on the Br, a "normal" equatorial Br–F bond, and electron-rich three-center F–Br–F axial bonding. BrF_3 is clearly related to SF_4 and XeF_2. A tellurium analogue (Figure 5) would be Te_4^{4-}.
>
> Let's look at the structure at hand in still another way. Each Te2, linear, is hypervalent and (if it were maximally hypervalent) could be assigned an electronic structure such as that shown in Figure 6, and a formal charge of –2. Each Te3 can be assigned a locally hypervalent structure (Figure 6) and a –1 formal charge. With these charges throughout the net we would have a charge per formula unit, $(Te3)_4(Te2)_2$, of –8. However, the actual charge is only –3! In other words, our Te_6^{3-} net is hypervalent (as the T-shaped Te3 and linear Te2 indicate), but it is not "maximally hypervalent" in the sense of as many electrons as these hypervalent geometries would allow. It is this intermediate reduction stage that makes the electronic structure of Te_6^{3-} truly nonclassical and requires a delocalized bonding description.

What annoys some reviewers about this section is that most simple of chemical intuitions, electron counting, here done in public.

There is much more in this paper: discussions of an alternative structure (see Figure 7) and possible fragmentations of the net, and the suggestion (on the basis of the computed electronic structure) of two unknown compounds, $[CsTe_6]^-[CsTe_8]^+$ or $CsTe_7$ and $[CsTe_6]^{3-}[CsTe_8]_3^{3+}$ or Cs_2Te_{15}. Both should have structures similar to that of Cs_3Te_{22}, but composed of layers of $CsTe_6$ sheets and $CsTe_8$ units in 1:1 and 1:3 ratios, respectively.

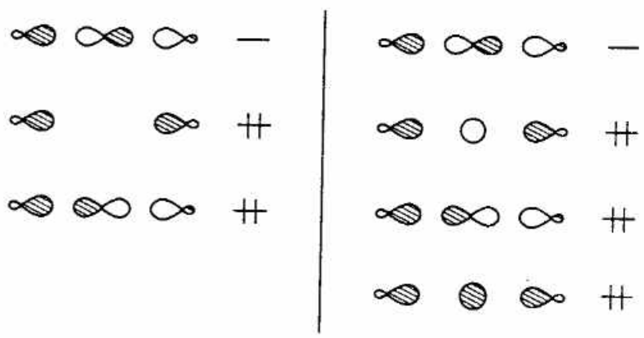

Figure 4. The orbitals involved in the three-center bonding in Te_3^{4-}, I_3^-, and XeF_2.

The $CsTe_7$ phase should be metallic. Happily, one of these compounds has been made, and it almost (not quite) has the simple structure we predicted.

Now I must rein in my enthusiasm for this wonderful molecule and return to the subject of this lecture. I do hope that by this example I have illustrated what I mean when I say that the rhetoric of teaching has influenced my research. And I hope to have enticed you to look at tellurium's weird and fascinating chemistry.

III

Now I turn to what I see as the reasons for talking to the public about science, and the difficulties of doing so. I do not mean to exclude personal and structural reasons. (By these I mean the sheer fun of the study of matter and its transformations, the fact that most of us are employed to teach chemistry—with attendant obligations, and that we do need to train professional chemists) These things we understand well. They may be fun or a chore, but they are intrinsic to our profession. I want to address in a more general, reflective way, the reasons why we must teach in the broadest possible way.

First, there is public and political concern about money spent on science. The public ultimately supports our research through tax dollars. The informed citizen will let the talented expert carry out his or her basic research. He will accept even that technological benefit is not guaranteed. Such a citizen will accept even a measure of vagueness about what is done and will take the excitement of the scientist as a sign of creative activity. For a while. But at some point we have to tell people (not the least among them being our parents and spouses) what it is that lures us back to work nights and Sundays; why it's thrilling to open a new issue of the *Journal of the American Chemical Society.*

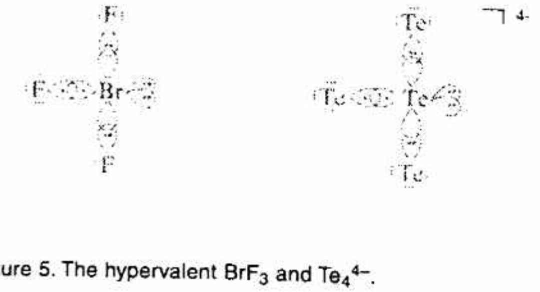

Figure 5. The hypervalent BrF_3 and Te_4^{4-}.

Figure 6. Maximal hypervalence in the Te_6 net would lead to a 2− charge on the linear telluriums (left) and a 1− charge on the T-shaped tellurium (right).

Second, chemophobia is rampant. There is a negative image of chemistry and chemists as the producers of the unnatural, the toxic. But at the same time, every survey shows that the public views scientists with high regard and trusts them. This is not irrationality, just nice human inconsistency. People are not machines. They can both value and be afraid of something at the same time. But certainly the more people know (of substances, of molecules) the less likely they are to be afraid of what we create.

Third, if we do not know the basic workings of the world around us, especially those components that human beings themselves have added to the world, then we become alienated. Alienation, due to lack of knowledge, is impoverishing. It makes us feel impotent. Not understanding the world, we may invent mysteries, new gods, much as people once did around lightning and eclipses, St. Elmo's fire, and volcanic sulfur emissions. I feel the growth of antirational movements (although to me religion is most certainly not one of these) in the form of cults and of interest in the occult and astrology. These are modern-day reactions to the mysteries with which science has surrounded human beings.

My fourth and last point of concern about chemical illiteracy and teaching chemistry concerns democracy. Ignorance of chemistry poses a barrier to the democratic process. I believe deeply that "ordinary people" must be empowered to make decisions—for example, on genetic engineering, waste disposal sites, dangerous and safe factories, and which addictive drugs should or should not be controlled. They can call on experts to explain the advantages and disadvantages, options, benefits, and risks. But experts do not have the mandate; the people and their representatives do. The people have also a responsibility. They need to learn enough chemistry to be able to resist the seductive words of, yes, chemical experts who can be assembled to support any nefarious position you please.

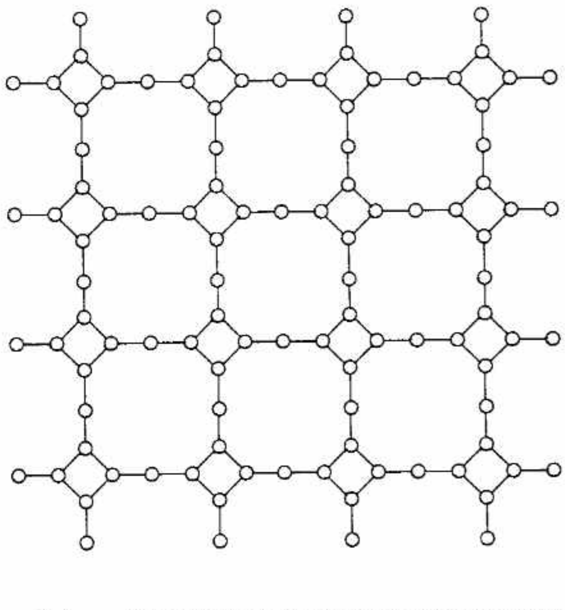

Figure 7. A possible distortion of the tellurium net to a hypothetical D_{4h} $Te_6{}^{3-}$ sheet.

There are diverse audiences for what we want to say:

- The children and young people in our schools,
  - who will be citizens and not scientists (99%),
  - who might be scientists; who may be motivated to become such by what we teach,
  - the small unknown subset who will decide the future of the country and of science.
- Not children, but
  - the proverbial general public, those who watch soap operas religiously and whose labors move the country on,
  - the politicians and authorities: and I don't necessarily have a bad view of them; I respect the compromises they must make and that I can avoid,
  - the merchants and business men and women who power our economy,
  - our friends in the arts and humanities and religion, the shapers of the spirit, and
  - other scientists.

It seems that each audience needs a different approach. It seems impossible to speak to all. But please don't despair. Every teacher has the experience that, as difficult as it seems, it *is* possible to speak to several audiences at the same time.

What are the problems we face in teaching science? What are the attitudes people bring to our subject? Let me describe some:

- Science is complicated, too difficult for a "normal" person to understand. Science is for smart people.
- Science doesn't concern me. It's not going to determine if Syracuse does or does not (it didn't) win the NCAA championship, or whether I can buy my beer (or VCR).
- Science is boring; it is definitely not fun.
- Science is done by rich people—old, white, European men with beards.
- Science is for people who don't want to talk to other people but would rather play with computers or things.
- Science creates the unnatural, the dangerous.
- Science kills the lovely hawk circling the sky and dissects him. Science is unpoetic, inhumane.

These are caricatures and extremes; but I think you recognize them, don't you?

One can attempt to counter these attitudes one by one. But I would rather make some observations that point to an approach rather than to a specific strategy.

- These are *perceptions* about science (mostly wrong), not realistic assessments. That's okay; we live by ideas and things of the spirit as much as we do by matter. Please accept the strength (and even sincerity) of a perception even when it is at some level wrong.
- What we do not understand, we usually find uninteresting and sometimes are just afraid of. What we understand, we may find interesting and may (not always) be unafraid of. This applies to art as well as science—think of attitudes to Stravinsky's music of the beginning of this century. And this is why we must teach, in myriad ways.
- People like facts; but they really love a good story, well told. Telling stories is very old. Stories are human. They are about perceptions. Through them a shared understanding forms.

So I think that one way into people's hearts and minds is to tell stories of science. In school it may be done in the midst of a logical development of a subject. To a general audience it's a way to normalize, humanize, science and build a piece of understanding. I urge you to explore the power of a story well told in your teaching.

IV

I return to the making of our video course, *The World of Chemistry*. The course was conceived by Isidore Adler of the University of Maryland and Nava Ben-Zvi of the Hebrew University of Jerusalem. A decade ago they approached the Annenberg/CPB project, which eventually funded the major part of this course. Adler and Ben-Zvi, together with University of Maryland physical chemist Gilbert Castellan, Margot Schumm of Montgomery College, and Mary Elizabeth Key, then of St. Albans School in Washington, formed the "academic team" that conceived the content and supervised the production of the programs. Richard Thomas was the imaginative executive director and producer of the series, working together with the able technical staff at the Educational Film Center, Annandale, Virginia, an Emmy Award–winning production company. This Pimentel award is for them as well. Sadly, Izzy Adler and Gil Castellan are no longer with us.

The World of Chemistry is intended for a junior college, four-year college, or remote-learner audience. It can serve as a complete course in chemistry, but it can also be used as a supplement for courses at any level, secondary school or university, as a resource for young people or industrial workers, or just as entertaining viewing for the citizen-at-large.

Each program contains the following components: (i) two chemists who appear in nearly all the segments: I myself, as the presenter or series host, and Don Showalter of the University of Wisconsin at Stevens Point. He has all the fun, since he gets to do the spectacular demonstrations. There are also (ii) one or two lively interviews in each segment, (iii) some computer animation (no blackboard!), and (iv) weaving it all together over fast-moving montages and footage illustrating the concepts taught, a narration.

Some of the programs teach very directly—so one of the 26 is on "The Mole", and two on "The Driving Forces" and "Molecules in Action", which explain on the macroscopic and microscopic levels why chemical reactions occur. Other programs describe important chemistries: chemistries of color, of metals, and of reactions on surfaces. There is a whole program devoted to "The Chemistry of the Environment".

In professional television, which is what these programs are, you get what you pay for to a certain extent. These programs were produced at a per-minute cost only half that of a typical U.S. *Nova* program, or only one tenth that of *Cosmos*. So whereas my friend and colleague Carl Sagan stood in front of the ruins of the library of Alexandria in Egypt, I got sent as far from Washington, DC, as Baltimore, Maryland, to stand on a wintry day on a tank car of sulfuric acid! Actually you'll see more in these programs than one might have judged from their cost. They were made with the dedication, sweat, and mental energy, mostly unpaid, of a remarkable team of people.

...in how many chemistry courses in the world does the instructor show students five minutes of steelmaking and three minutes of the Hall process?

One observation that I would make is that what started out as a weak point of the production turned out to be one of its great strengths. We did not have the money to shoot 10 to 15 minutes of each half-hour from scratch, (i.e. illustrating through our own filming the concepts what we wanted to teach). So we made do with skillfully edited "stock footage". This is a euphemism for free or inexpensive film clips obtained from government or industrial sources. An industrial public relations consultant could often identify the source of a scene from the five seconds it is on the screen. Now this stock footage could have been a weakness. It isn't what we would have done in that ideal, unlimited-budget world of which every film maker dreams. But by being forced to use (fairly, without commercialization) scenes supplied by others, especially by industrial sources, our programs acquired a "real world" feel. I can put it another way: in how many chemistry courses in the world does the instructor show students five minutes of steelmaking and three minutes of the Hall process? We do, and the visual impact is tremendous.

I want to make some observations on the tensions I see arising in the use of television to teach.

First, a philosophical question: can one teach via television? Or does a switch go on in our minds that this is entertainment?

Second, the process is incredibly expensive. So much of one's time is spent in fund-raising. But this is as typical in the arts as it is in science. My friends Ivan Legg and the late Paul Gassman worked very hard on raising the funds to a sequel to *The World of Chemistry.* We failed. The industrial community, our own industry, was not supportive of our efforts.

Third, the television medium is inherently journalistic. As such it leads to excessive mythologizing of individuals and of the way things happened. This hurts.

Fourth, there is the continuous treachery of simplification, of making little compromises. In the end it doesn't leave the person making those compromises (me, and maybe I was too sensitive) feeling good about either himself or the process.

Finally, the power of images is incredible, so there was a temptation to be driven by images, which at times did violence to the real intellectual achievement of chemistry—the slow but ingenious marshaling of indirect evidence to build a framework of incontrovertible reality for molecules and their transformations. Chemistry is the most marvelous example I know of knowing without seeing.

But it was worth it! I am proud that we created the first video course in chemistry ever made. The credit for the programs goes to our team, whose members' names I've mentioned above. I wish they could have shared in this award.

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It is time here to reassert my confidence in what we do. We teach chemistry: the art, craft, science, and business of substances (now known to be molecular) and their transformations. We introduce young people to the molecular science, awakening in their minds the ability to deal with the balance of simplicity and complexity that characterizes chemistry. We believe (I feel confident it is not only I who thinks this way) that chemistry instruction at every level must be done in the context of a liberal arts education, fighting compartmentalization all the way and connecting chemistry to economics, literature, history, society. To *culture* in the broadest sense. We believe that the student is best served by consistently being led to value discovery and true understanding. It's not easy, but there is nothing I love more than teaching. As you do. Thanks for honoring me with the Pimentel Award!

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Four Important Functions:

...from the *Journal*'s first issue.

1) To act as a medium for bringing before chemistry teachers the timely papers given before the Division of Chemical Education of the American Chemical Society and other valuable papers of like nature and thereby conserve any worthwhile work done in Chemical Education.

2) To encourage community of effort in any instituted reforms, furnishing a medium through which significant reports, studies, and experiments will be given wide circulation.

3) To encourage sufficient research among the teachers so that the proper investigational atmosphere may prevail in our classrooms.

4) To keep the teacher and student in closer touch with current opportunity furnished by the American Chemical Society and other scientific organizations and institutions.

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