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A MODERN AND QUANTITATIVE PRESENTATION OF  
GENERAL CHEMISTRY

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The day that the first earth satellite was launched, it became fashionable to raise one's voice in a cry of alarm over the shocking state of the American educational system. I do not need to add my voice to this chorus or to suggest additional candidates for the role of THEY who are responsible for the mess we are in. Practically all the various groups have already been singled out for attack.

*The colleges and universities:* they have been coddling the students, and directing their own efforts toward building buildings instead of building men's minds.

*The students:* they are lazy, and are both unwilling and unable to put forth an honest intellectual effort.

*The parents:* they have failed to develop in their offspring a proper sense of values and have abdicated their traditional role of models to TV and Elvis Presley.

*The professional educators:* by insisting that "how to teach" is more important than "what to teach," they have built an empire that is concerned only with perpetuating mediocrity.

*The school boards:* their lack of courage in the face of pressure groups has sapped the morale and driven thousands of imaginative minds out of the school system.

There is a great deal of truth to many of these charges, and it is a pity that courageous souls such as Joel Hildebrand, who have been telling us these things for years, were completely ignored until a Russian space dog started circling the earth. But, however true these charges may be, I am not willing to jump to the "obvious" conclusion: that the American system of education is in crisis and that it is inferior to other systems of education. Last year I was a visiting lecturer in France and I had ample opportunity to observe rather closely the workings of the "superior" continental system of university training. The completely unexpected conclusion I eventually reached—even with its curse of monstrous numbers, the American system of education is turning out a product which for imagination, curiosity, and ingenuity, is unrivaled in Europe. I think the American system is vigorous, healthy, and worthy of respect, and those who condemn it are paying too much attention to those who put a premium only on one's ability to perform mental gymnastics.

Not that we can afford to be complacent or that we can do without some improvement! There's room for quite a few giant steps and we as chemistry teachers can touch some of these off. One of the puzzling aspects of the general fault-finding and soul-searching that has been going on in the past six months is the apparent immunity of the teacher. If ever the stage were set for the "poor overworked, underpaid" teacher to become complacent, this is it. Actually, let's face it! If anyone is ever going to do anything about improving the American system of education, then it will have to be the teacher who does it. And the beauty of it is the teacher can do something constructive right away whereas, by the time the professionals come up with an answer to this problem, another problem will have taken its place. What I advocate (and this is the essence of what I have to say) is that we as chemistry teachers can do a lot to improve the American system of education simply by raising the standards in our courses and toughening them up. We have tried it at Cornell in our big freshman chemistry course and it works.

Every teacher is faced by a decision—what level of work should I ask of my students? How much material should I expect them to be able to handle? We posed these questions in overhauling our general chemistry course. The answer we suggested—let us ask our students to do a bit more than we think they can handle. Let us see how far we can push them. The amazing result—the more we asked of the students, the more they gave us. And they seemed to be better satisfied in doing so. The net result is that now our big freshman chemistry course sets a higher standard as a modern, quantitative presentation of general chemistry than many a course given to chemistry majors.

Certainly the increasing complexity of physical sciences demands that we put more into the freshman courses—more facts (for efficient operation) and more principles (for dealing with more complex unknown situations). Why do we hold back? The common answer is "the students can't take it. They are not so well-prepared as previously. We have to go slower." On the contrary, college students are better prepared to grasp ideas than they were previously. Also, they resent being coddled. Such treatment, when inflicted on them, embarrasses them. I'm sure other people have discovered this same thing—if we want college students to act like students we must treat them as students and not as children!

Furthermore, there are other ample justifications for higher standards and

tougher courses. One of these is sheer self-preservation. Freshman chemistry has become such a monster (always something being added, never anything taken out) that it is absolutely unmanageable unless there is a drastic overhaul in the direction of using to the full the powerful summarizing principles that a chemist uses as second nature. Another justification is that toughening our courses is about our only effective leverage on the high schools. So long as we make concessions to the high-school preparation and take over the instruction which rightfully should have been done in high school, the situation will get worse. Only when the high schools realize no remedial action will be taken at the college level (to plug holes in arithmetic, algebra, general science, etc.), then only will entering students come in with the proper skills.

What, then, does Cornell do in presenting a modern, quantitative course in freshman chemistry? First, the background. We have three courses (1) a terminal course devoted to those who want to know something *about* chemistry but who will take no further courses in the field, (2) an accelerated course including qualitative analysis for chemical engineers and those definitely decided to be chemistry majors, and (3) an introductory course which assumes no previous knowledge of chemistry but which eventually serves as prerequisite for following chemistry courses. This third course is by far the largest (1100, compared to half as many in the other two combined) and is the one which concerns us here. On the average it breaks down into 400 engineers (mechanical, electrical, civil, and engineering physics), 250 agriculture students (those who will need more chemistry, as in soil science, dairy industry, etc.), and 450 arts students (pre-meds, undecided chemistry majors, and humanities people in search of broadening themselves). The backgrounds range all the way from no previous chemistry to two years of rather high-level experience in high school. The course is presented as two 50-minute lectures per week (in groups of 350) and one 3-hour laboratory-discussion per week (in groups of 20).

Our philosophy has been to teach chemistry (fundamentally on a framework of principles) as it really exists to a modern-day chemist—that is, the choice of terms, models, and beliefs is what we think chemists hold to be true at present. By the same token, those points where chemists are now uneasy are also mentioned. The other guiding principle has been to teach in such a way as to require no unlearning in a subsequent course. For example, the material on gases includes enough on nonideal behavior so that a nonideal gas will not come as a shock in physical chemistry as it did to many of us. The other main principle in our philosophy is to emphasize the distinction between “a fact that is observed” and “a property of a model that is being used to explain that fact.” We believe that much of the trouble in making the transition from high school to college and from freshman courses to following courses stems from a failure or inability to distinguish clearly between a fact and an explanation. Many are the students who have come to me with the remark “then what my high school teacher told me was wrong?” In most cases, the student is referring to a property of an outmoded model (for example, the circular tracks of the electrons in the planetary model of atoms). In his confusion of “explanation” with “fact” he believes he is being asked to throw out facts—certainly a demoralizing prospect.

Throughout the course, our approach is quantitative, with a considerable emphasis on problem-solving and on giving, so far as some severe limitations permit, a quantitative expression to the properties of some of the models (e.g., kinetic molecular theory). In order to make the quantitative approach feasible, we have introduced two innovations to take the burden off the usual assigned problem sets and exercises. One of these has been to section the students for their discussion-laboratory periods according to mathematical ability. During the first week of the course, the students take an examination covering in part simple arithmetic and algebraic operations and in part so-called word problems. From the results of these tests, the students having laboratory at a given time are separated so that

the top 20 are in a section by themselves, the bottom 20 in a section by themselves, and the rest are distributed at random. The reason behind such sectioning is that it permits the low section to concentrate on simple mathematical aspects which are of no interest to the top section. On the other hand, the top section can spend its discussion time on more sophisticated topics. Feeling as we do that we owe a special responsibility to keeping our good students working to the limit of their capabilities, we assign senior staff men to lead the discussions in the top sections with the strong implication that they will push the discussion as far as possible. Thus, the top students are not inflicted with the 20-minute discussions of how to read a graph or what a logarithm is that the poor students find so interesting. Similarly, in his own milieu the poor student is not bashful about asking the simple questions that honestly bother him (and probably his fellow students).

The other device for increasing mathematical competence is the problem session. At strategic places in the course, laboratory experiments are replaced by organized but informal problem-solving sessions at which students work at the blackboard on a mimeographed set of interrelated problems. The instructor is always there to give immediate assistance where needed. These sessions have proved to be immensely popular. Certainly they are useful because they have allowed us to add quantitative depth to our course. A not unwelcome dividend is that the problem sessions add flexibility to the laboratory scheduling problem, particularly when the lecture material for several consecutive sessions does not lend itself to experiments (e.g., atomic theory).

As far as the material covered is concerned, we spend the first term in developing the principles of chemistry in order of increasing complexity—the atom, the chemical bond, states of aggregation, solutions, kinetics, and equilibrium. A surprisingly large body of descriptive material can be woven in as illustrative material, and I suspect that by using to the fullest extent the organizing principles, our students end up with as much knowledge of descriptive chemistry as if they had taken a traditional course. (This point may be important in trying to sell a principles approach to the engineering and agriculture administrators.) In the second semester, the chemistry of the elements and their compounds is discussed at a rather high level in terms of the principles previously developed. The order is hydrogen, oxygen, aqueous solutions, and then from left to right across the periodic table. We have abandoned the traditional right to left treatment for several reasons. First of all, group similarity is much more strikingly illustrated by the alkali metals than by the halogens. (For the halogens, I often get the feeling the similarities and group trends are more pronounced in the text books than they are in the laboratory. Rare is the student who comes out of freshman chemistry with a correct idea of the chemistry of fluorine, for example.) Secondly, it is convenient to have metallic properties highlighted first so that it does not become necessary to interrupt the discussion later with perhaps the false implication of a clean-cut distinction between metals and nonmetals. Thirdly, beginning with metals has the advantage of getting rapidly into elements generally unfamiliar to most students. They stay more interested early in the semester because of the unfamiliarity of the metals and can be kept interested later in the semester since the familiar elements such as sulfur and the halogens can be given more sophisticated treatment.

Actually, to appreciate the coverage in a course one needs more than an indication of topics covered. As an example of what we do, we can look at our treatment of chemical kinetics—almost invariably a mistreated subject in freshman chemistry courses. First of all, we keep a clean separation between kinetics and equilibrium so as to forestall the common misconceptions when these are treated together. In treating kinetics, we do not shirk the real problems as is often done by taking nonrepresentative cases. We face up to the full problem. Our approach, as customary, starts with the observed facts of kinetics—the fact that rates depend

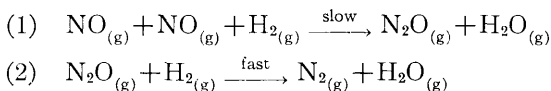
upon factors such as concentrations and temperature. As a specific example we take the reaction



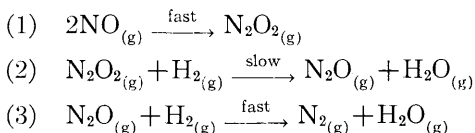
for which the rate law is

$$\text{Rate} = k[\text{H}_2] [\text{NO}]^2$$

[It might be noted that we avoid that old tired horse of hydrogen plus iodine to give hydrogen iodide—one of the few cases for which the rate dependence agrees with the stoichiometric equation. Better we should face our students with early recognition of the fact that in general the rate law exponents are not deducible from the coefficients of the stoichiometric equation.] Then we proceed to discuss the elements of collision theory and how the observations can be interpreted. The idea of stepwise reaction with one step acting as a rate-determining step is not ignored and in fact actual mechanisms are proposed for the above reaction. For example, we indicate that the above rate law would be consistent with the following steps:



where (1) is rate-determining. However, we point out, many people object to this mechanism because it requires a three-body collision (2 molecules of NO and 1 molecule of H<sub>2</sub>)—a rather improbable event. Some people, we say, prefer the following steps:



which, after all, add up to the same net reaction but do not involve a three-particle collision. Then, by using the fact that the rate of step 2 is proportional to the concentration of N<sub>2</sub>O<sub>2</sub> times the concentration of H<sub>2</sub> and that the concentration of N<sub>2</sub>O<sub>2</sub> is directly proportional to the square of the concentration of NO (step 1), we can come out with the observed rate law. Needless to say, our presentation is not on a very sophisticated level but it does put the essential points across and it does not breed a host of misconceptions that will need to be unlearned in following courses.

What about the laboratory? Here our thoughts have been bounded by considerations of space and money limitations. Obviously one thinks twice before requiring a fifty-cent item for a student when it must be multiplied by 1100 students. This is one of the reasons qualitative analysis has not been made an integral part of our second term laboratory. Instead, what we have tried to do is to draw on a large number of quantitative experiments—using where possible the added stimulus of unknowns. Thus, for example, we ask our students to determine the atomic weight of an unknown metal, which they do by determining its gram-equivalent weight. This is straightforward and is a classical experiment. But they need the specific heat. Instead of giving them the value, we have them determine it by a simple calorimetric method. The result has been that an experiment previously “dry-labbed” now takes on a personal character for each student since only his instructor knows the identity of his unknown.

Similar modifications have been made in other classic experiments. For example, instead of doing an experiment to “verify” Boyle’s and Charles’ laws we have our students extend the same experiment so that they determine absolute

zero. They get amazingly good results and, what's more important, feel as though they were really doing science. Another experiment involves the study of the rate of iodide-catalyzed decomposition of hydrogen peroxide. Unlike the classic iodine clock, which gives an integrated time that is almost impossible to interpret, the hydrogen peroxide decomposition enables the student to measure the oxygen at successive intervals as it is being evolved, thus enabling him to extrapolate back to zero time and find out how, for example, changing the initial concentration of iodide changes his results. The idea of a rate law takes on a real meaning. Other experiments are similarly quantitative and include such things as analyzing an unknown for sulfate content, determining what happens to the oxidation number of sulfur when  $S_2O_3^{2-}$  reacts with  $I_2$  to convert it to  $I^-$ , analyzing soap for water content, determining what fraction of burning magnesium goes to  $Mg_3N_2$  and what fraction goes to  $MgO$ , etc. All of these experiments are done with usual freshman equipment, but the precision in many cases is startling. To us it indicates that in the laboratory as in the lecture when students are challenged, they produce better than we expect them to.

Well, what have been the results of our tougher, stiffer approach? First, the course has gained increased stature among the student population. Students now say, "It was a tough course but I enjoyed it," instead of merely shrugging their shoulders as they did previously. Second, it has resulted in an increased effort on the part of the students. I sometimes suspect that the average student will do 75 percent of anything you ask him to; so, you had better ask a lot more than you really want him to do. Thirdly, there has been an increased interest in chemistry as a major. About half of our chemistry majors come from this large course and apparently are drawn mostly from those who are undecided between chemistry and physics. Toughening our course has made chemistry more appealing to those who are attracted to the elegant precision of physics. Fourthly, the morale is better among our teaching assistants. They work harder but with more motivation. It is true that many graduate students come to us so poorly prepared that as teaching assistants they find it difficult to keep ahead of the freshmen. But their invariable remark—"I wish I had a course like that as a freshman." Finally, the gratifying result is that the idea is spreading to other courses. Physics and zoology are tightening up their introductory courses and even the agriculture school is getting concerned about raising standards.

Not that we imply all our problems as being resolved. We still have not solved the problem of how to ease the painful first 6 weeks for the student who takes our course without any previous experience in chemistry. He has a rugged time of it at first (primarily, I think, because of the demand of quickly developing a large specialized vocabulary). My only satisfaction is in the observation that these students usually turn out eventually to be better than average—possibly because the pressure is on them to develop good study habits early. The other unsolved problem is what to do with the students who come to us with extremely good high school preparation. Obviously, you say, give them advanced standing. This we try to do, but there are two odd problems. Most of those who get advanced standing do not take advantage of this by starting in with an advanced chemistry course (in other words, we never get a crack at them as potential chemistry majors), or they refuse to take advantage of the possibility of getting advanced standing. It is an unfortunate thing that many of our students are so used to playing it safe that they are more willing to be bored for a whole year and get a good grade than to try something daring and run the risk of failure.

There are other problems which I foresee for the future which may be more serious. One is technical and involves the supply of teaching assistants. If the government, as it seems probable, steps up its fellowship program significantly, then we shall be faced with the awkward situation of having the good graduate students not available for teaching duties. A possible solution is to require each

fellowship holder to teach for 3 hours. This will be inefficient because preparing to teach one laboratory section takes as much time as preparing to teach three laboratory sections. An alternative solution would be no fellowships for first year graduate students. The other problem is more general and probably less likely to be solved. It is summed up in the description given by Dr. Polykarp Kusch, Professor of Physics at Columbia and Nobel laureate in 1955, after a visit to Dartmouth College as a visiting professor. After lecturing to a class of 180 undergraduates, he described his impression as follows, "one-third had a deep, lively interest; one-third had good manners; one-third had neither." Evidently some of these people don't belong in college. I'm not sure I want to commit myself on which of the last two groups is dispensable.

In conclusion, I would like to make a special plea to chairmen of chemistry departments—a plea not to consider freshman chemistry as "taken care of" if it causes no administrative trouble. Aside from the fact that tuition-wise it usually brings in the biggest chunk of money, freshman chemistry merits special consideration for two reasons: (1) it is *the* course in which the future attitude of the country toward chemistry is being shaped and (2) it is *the* course in which we have the most direct possibility of strengthening the future quality of our profession as chemists.

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