# Why Changing The Curriculum May Not Be Enough

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### Introduction

Since 1983, more than 300 major policy studies on mathematics and science education in the United States have been released (*1*)—an average of almost one per week. This recent concern about the state of science and mathematics education is not unique. The 20th century has been characterized by a cycle of short bursts of attention to the problem of scientific literacy at times of crisis, followed by long periods of complacency. Whatever the source of the perceived threat that produced the sense of crisis, the response is always the same: something is wrong with the way science is taught, and we need to restructure science education.

It might be useful to examine the way scientists and science educators historically respond to the notion that science education is in a state of crisis. They typically take three approaches: (1) they recommend restructuring the curriculum; (2) they increase efforts to attract young children to science; and (3) they try to convince public school teachers to change the way science is taught at the elementary and secondary levels.

These are all necessary components of any resolution of the present crisis. There is reason to question, however, whether they will be sufficient. History has shown that revising the curriculum is not enough, and demographics has shown that the problem is not the number of children interested in careers in science, but the hemorraghing of the scientific pipeline that occurs when these students encounter science and mathematics courses at the secondary and tertiary level (*2*). Changing the curriculum—the topics being taught—is not enough to bring about meaningful change in science education, we also need to rethink the way the curriculum is delivered. For those of us who teach at the college/university level, this process might be facilitated by listening to elementary and secondary teachers, who have developed valuable tools to achieve this goal.

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### How Did We Get Where We Are?

The chemistry, physics, and mathematics courses I took as both an undergraduate and a graduate student had the same format. They consisted of lectures, during which the professor talked and the students listened. (If they came.) Reflecting on her experience in chemistry, Patricia Metz described one course as follows: "At times I felt the professor's notes became my notes without passing through either of our minds" (*3*).

The mode of instruction that dominated the science and mathematics courses I took is a linear descendant of a system introduced in medieval universities: a series of lectures in which scholars summarize the state of knowledge in their area of expertise. Lectures are still the best way to introduce information when our role is the same as that of the "masters" who taught at the early universities; when we bring together information from a number of sources to which the audience does not have access. But that is not the case in general chemistry courses, where students have access to excellent texts that provide them with more than enough information.

The present mode of instruction sends a clear signal to the students that they don't have to read the textbook. (A cursory examination of the books sold back to the bookstore at the end of year suggests that they often don't.) All they have to do is come to class, we will read the textbook for them. Does this approach work? There is abundant evidence to suggest that it does not.

### What's Wrong with What We Are Doing Now?

Twenty years ago, a paper entitled "The Grim Silence of Facts" was published (*4*), which began as follows: "While grading a beginning graduate inorganic examination some time ago, I was startled to discover that the student believed silver chloride to be a pale green gas." This year, a paper appeared that described results obtained when a conceptual knowledge exam was given to beginning graduate students (*5*).

The results obtained with the conceptual knowledge exam provided additional evidence that misconceptions are resistant to instruction. In spite of the 500 hours of laboratory and 400 hours of lecture that characterize the undergraduate experience in chemistry mandated by the ACS Committee on Professional Training, a small but significant fraction of the graduate students appeared to hold the same misconcepts that children bring to science (*6*). There was also clear evidence that the students often held knowledge without understanding. Furthermore, the students were virtually unable to apply their chemical knowledge to the real world.

Twenty years ago, Gil Haight told me that one source of confusion in the minds of chemistry students is the fact that they must work in two different worlds: a macroscopic world in which they do experiments and a molecular world in which they interpret their data. Fifteen years ago, Dudley Herron told me that students get confused because there is a third world in which they have to work: a symbolic world, in which the symbol "Na" sometimes stands for a shiny metal that reacts vigorously with water and other times for an infinitesimally small particle that contains 11 protons, 12 neutrons (most of the time), and 11 electrons.

With due respect to both gentlemen, I believe the problem is more complex. In addition to the macroscopic, molecular, and symbolic worlds they encounter in chemistry courses, students also work in a real world that seems to have no relationship to what they learn in chemistry. If our graduate students can give the answers cited in the conceptual knowledge paper, it is reasonable to assume that students who stop after taking general chemistry are also incapable of applying their knowledge of chemistry to the world in which they live.

## Chemistry as an Intellectual Process, Not a Product

Tobias quotes the following response from a chemistry professor whose course had been described as dull (*1*, p 55): "It is dull. It is dull to learn, and it is dull to teach. Unfortunately, it is the basic nuts and bolts stuff that must be mastered before anything useful can be accomplished ...". For some, the solution to this problem is to change the material that is taught. Experience has shown, however, that this alone does not solve the problem. It is not just the topics being taught that makes chemistry dull, but the way they are taught.

Many conscientious teachers take the responsibility for learning onto themselves. An observer in their classroom might report the following.

1. The structure of the course seems to reflect the belief that if the instructor does not discuss a topic in class, the students can't be expected to learn it.
2. The instructor concentrates on building basic skills.
3. Little (if any) attention is paid to convincing the students that these are important skills to develop.
4. While focusing on the skills students need to develop at one point in the course, no effort is made to provide an overview of how the topics in the course fit together.

Consider what would happen if you put the following question on the final exam in the second semester of a general chemistry course.

> A significant fraction of this course was devoted to calculations based on equilibrium constants, such as the acid-dissociation equilibrium constant for a weak acid,
>
> $$K_a = \frac{[H_3O^+]\,[CH_3CO_2^-]}{[CH_3CO_2H]}$$
>
> the solubility product equilibrium constant for an "insoluble" salt,
>
> $$K_{sp} = [Ag^+][Cl^-]$$
>
> or the complex formation equilibrium constant for a coordination complex.
>
> $$K_f = \frac{[Cu(NH_3)_4^{2+}]}{[Cu^{2+}]\,[NH_3]^4}$$
>
> Describe three ways of measuring the value of one of these equilibrium constants.

Students who can successfully do $K_a$ calculations won't necessarily know how to determine $K_a$ from a plot of pH versus the volume of added base. Students who have mastered the skill of using the Nernst equation to calculate the potential of an electrochemical cell at nonstandard-state concentrations won't necessarily recognize that potential measurements for a carefully chosen set of half-reactions can be used to measure an equilibrium constant for a reaction that does not appear to involve the transfer of electrons, such as the value of $K_{sp}$ for AgCl. Students who have mastered the skill of calculating $\Delta G^{\circ}$ for a reaction from tables of $\Delta H^{\circ}$ and $S^{\circ}$ won't necessarily recognize that the product of this calculation can be useful.

It would be a mistake to spring questions such as this on the students at the end of the year, if epistemological issues had never been discussed in class. But it is an equally serious mistake to ignore such issues during the time spent with students in class. The first time I raise this particular question in my class, I start by asking: "Where do equilibrium constants come from?" The students answer: "From the back of your book!" By the end of the semester, at least some of these students begin to understand—and more importantly, appreciate—the link between the topics in the second-half of my general chemistry course. For these students, at least, chemistry is anything but dull. For them, chemistry is not an endless string of meaningless calculations, but a series of techniques that can be used to extract information whose importance they are beginning to recognize.

## The Difference between Teaching And Learning

There is a subtle difference between theories of learning and theories of teaching. Theories of learning describe how an organism learns; theories of teaching deal with the ways in which we can influence what the organism learns. It is important to distinguish between the two for the following reason: Teaching and learning are not synonymous; we can teach—and teach well—without having the students learn (*7*).

On the top shelf of bookcases that line my office is a three-ring notebook, which contains a set of typewritten lecture notes from my first year as a college professor, 20 years ago. One of the topics covered in the course was molarity. The notes for this part of the course start by distinguishing between the concepts of solute, solvent, and solution. They then define molarity as the number of moles of solute divided by the number of liters of solution and conclude with a series of carefully constructed exercises, which show how this concept is used. I felt good about how I taught this topic, and my students reacted well to my teaching. In spite of this, roughly half of the bright, hard-working, science and engineering majors in this class at the University of Illinois could not solve simple molarity problems when they appeared on the hour exam.

## The Difference between Active And Passive Learners

Anyone who has struggled to achieve some mastery of chemistry should be willing to accept the following generalization: Active students learn more than passive students. Examples of this phenomenon abound. Thousands of hours of watching college and professional basketball, for example, has had no effect on my ability to play the game. There is no doubt that watching others can provide valuable hints about the skills we should develop, but nothing can replace time spent practicing these skills on our own.

Although chemists accept the validity of the generalization given above, they don't always recognize its implications. Reflect, once again, on your experience as an undergraduate. At some point, someone did to you what I used to do to my students: they defined molarity as the number of moles of solute divided by the volume of solution, and then worked a series of molarity problems for you. What did you learn from this discussion? As a result of listening to your instructor, were you able to do molarity calculations on your own?

Many years ago, Dudley Herron developed a technique for helping students in his remedial course invent the concept of molarity (*8*). He starts by demonstrating what happens when a pair of colorless solutions are mixed to give a colored precipitate and asks the students to help him write a balanced equation for the reaction, such as the following.

$$Pb(NO_3)_2(aq) + 2\ KI(aq) \rightarrow PbI_2(s) + 2\ KNO_3(aq)$$

The students are then asked: "How would you predict the amount of $PbI_2$ produced in this reaction?"

The first time students are asked to participate in solving a problem in class, there is often no response to questions such as this. Because Herron's students are used to being asked questions of this nature, one of them often suggests weighing the solutions before they are mixed, so that grams of $Pb(NO_3)_2$ and KI can be converted into moles of these reagents. At this point, most instructors would be tempted to tell the students why this wouldn't work. Herron asks the students to tell him whether it would work. Another student often notes that it won't work, because he started with mixtures—solutions of $Pb(NO_3)_2$ and KI dissolved in water—not pure substances.

If this doesn't happen, he can ask the students to reflect on what makes this calculation different from those they have worked previously, in which one pure substance reacts with another. Once the students recognize that the demonstration uses solutions of a reactant dissolved in water, the class can turn to the basic question: "How can I describe these solutions?"

One of the students often suggests determining the percent by weight of $Pb(NO_3)_2$ and KI in the solutions, and basing the calculation of the amount of $PbI_2$ formed on this information. When the class is asked to list the advantages and disadvantages of doing this, the discussion inevitably leads to the suggestion that it would be easier to measure the volume of a liquid than its weight. Thus, it would be easier to manipulate the solutions if they were described in terms of the weight of the solute in each milliliter (or liter) of solution, instead of using percent by weight. This is accepted as a viable description, but one that requires a subsequent conversion to moles of solute. With little (if any) explicit guidance, the students conclude that the solutions should be described in terms of the moles of solute dissolved in each milliliter (or liter) of solution. At that point, a formal definition of molarity is introduced.

There are several advantages to this dialogue between the students and their instructor (*8*).

1. It starts with a concept that makes sense to the students.
2. It builds from their understanding toward ours.
3. It shows why chemists use molarity, instead of other approaches that might seem preferable to the students.
4. It shows that chemical knowledge is a product of rational thought, not arbitrary rules to be accepted on the basis of authority.
5. It produces a concept that is meaningful to the students.

The role of both the students and the instructor in this classroom differs from the classical model of instruction. Students in this classroom are active learners, not passive recipients of knowledge that is neither understood nor assimilated. The instructor is not there to provide answers, but to guide the discussion among the students in the direction it must ultimately lead.

This activity was designed for a remedial chemistry course, and it works best with students who have not had chemistry previously. If you use it in a college-level course for science and engineering majors, someone in the front row will short-circuit the discussion, providing an answer constructed from prior experience. An alternative approach should work with this group of students. Start with the same demonstration, mixing solutions of $Pb(NO_3)_2$ and KI. Ask the students to identify the solute, solvent, and solution in each case and describe how they made their decisions. Then ask them to list different ways of specifying the ratio of the amount of solute to the amount of solution. Don't let them stop until you have at least three approaches: weight percent, volume percent, and molarity, and demand that they explain what they mean by each of these terms.

Now ask the students to explain *why* molarity is used so often to describe the concentration of solutions, instead of other ways of approaching the problem. Those students who have knowledge without understanding will be challenged to explain their knowledge. Ultimately the class should go through the same process of construction as the remedial group described previously, and the advantages listed above will be achieved.

### Finding Enough Time To Cover the Material

Every time this dialogue is used as an example of an alternative approach to instruction, someone in the audience says: "If I use this approach, I'll never have enough time to cover the material." They're right. Anyone who uses this technique will be able to cover only a fraction of the material that could be covered in a classical lecture. There is evidence to suggest, however, that doing less in class—but doing it well—might have a beneficial effect.

A recent article on cooperative learning (*9*) described the results of an experiment done by Patricia Metz (*3*), in which students in a general chemistry course were divided into two groups, each of which attended class in a different room. One group experienced a classic lecture course, where student–teacher interactions were kept to a minimum. The instructor of the other section tried to maximize student involvement, while minimizing his own. The performance of the two sections on the exams, which were written by the instructor of the lecture section, were almost identical, but there were clear differences in the attitudes of the students.

One of the results of this experiment bears repeating. In spite of the fact that less material was covered in the interactive class, the students in that class were more likely to indicate that adequate material was presented in class to prepare them for exams.

### Cooperative Learning

The interactive class described in the previous section is a form of cooperative learning, in which the role of the instructor shifts from "someone who teaches" to "someone who facilitates learning". Research on cooperative learning, which has been discussed elsewhere (*9*), has shown that student achievement is enhanced when students work together in a cooperative learning environment.

The constructivist theory of knowledge (*7*) offers an explanation for why this happens. First, and foremost, this theory assumes that the responsibility for learning ultimately rests with the individual learner. This can be facilitated by providing a format in which the learner must examine, clarify, describe, compare, and then negotiate with others the implications the individual ascribes to his or her experiences. Although learning occurs within the mind of the learner, anyone with classroom teaching experiences knows the value of being placed in an environment where knowledge has to be explained to others.

### Teaching by Listening

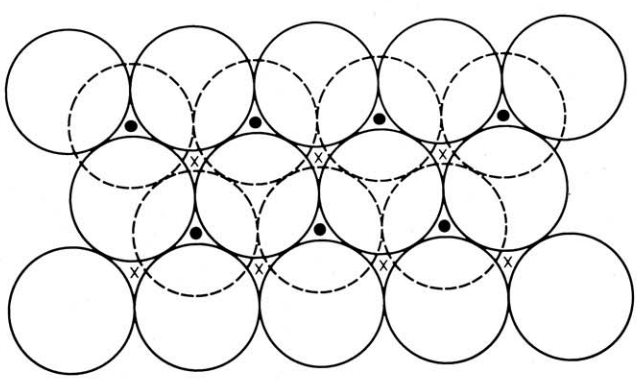
In a paper on the constructivist theory of knowledge (*7*), I noted that AT&T has changed the language they use to describe certain common items. A telephone is now a "voice terminal," and a telephone jack is an "information output device." In that paper, I argued that one of the problems with education is the fact that teachers focus on the development of their information output devices and neglect their information input device. Dudley Herron made a similar point when he stated: "The single most important impact research in learning has had on my own teaching is the portion of the time I spend listening to what students say" (*8*).

In his paper, Herron gave a concrete example of what he means by his statement in the form of a dialogue between an individual student and a teacher. Let me give a concrete example of how the same approach can be used to change what happens in a classroom in which the instructor feels it is impossible to enter into dialogues with individual students.

When I first came to Purdue, Bill Robinson convinced me that we needed to increase the amount of material on the structure of solids in our general chemistry course for science and engineering majors. Over a period of three years, a series of slides were developed to achieve this goal (*10*). One component of this slide program describes the structure of simple ionic solids. Let me briefly summarize some of the arguments used to set the background for this particular concept.

1. Negative ions are larger than neutral atoms and positive ions are smaller than the atoms from which they form.
2. Negative ions therefore tend to be significantly larger than positive ions.
3. As a result, simple ionic compounds often crystallize in a structure in which the negative ions pack to form a closest-packed array, such as a hexagonal closest-packed structure.
4. The positive ions pack in holes between the planes of negative ions that form this array.
5. As you can see from the figure, there are two kinds of holes in this structure, which are marked with "x's" and "o's."

When I first taught this material, I would ask the students to focus on the holes marked with "o's" in the figure, and I would tell them the number of negative ions that touch—and are therefore coordinated to—the positive ions in these holes.



Two-dimensional diagram of the three dimenaional structure of an ionic solid.

One day, instead of telling the students the answer, I asked them: "If you were a cation in one of these holes, how many anions would you touch?" I then took a vote. What fraction of the students thought the correct answer was three? Four? Five? Six? The answer was obvious to me, and it should be obvious to you. I would therefore ask you to cover the next paragraph with the palm of your hand and write your answer in the margin of this paper.

The results I obtained were fascinating. The majority of my students, who have a very good background in mathematics, thought the answer was five. This answer is absurd, if you assume the ions are spherical. It was so absurd that I couldn't figure out how any of my students arrived at this number. After lecture, I realized what happened. The students assumed that the positive ion packed in the hole between three anions within a given plane and then touched one anion in the plane above and one anion in the plane below.

This is impossible, of course. Any spherical anion small enough to pack in the infinitesimally small hole between three anions in a given plane could not possibly touch the anions in the plane above or below. Although I had clearly stated that the positive ions packed in holes that lie *between the planes of the anions*, the students tried to incorporate the cations in the same plane as the anions.

If I had not become convinced that I need to listen to what students say, I probably would have spent much of the remainder of my career telling each year's class the answer to a question they did not understand. Once I started listening to students, I recognized that I had structured my presentation of the material from my experience, not from theirs.

What do I do now? I cover the material outlined in the five points above. I then ask them the same question and get the same absurd answer. But now, without commenting on their answer, I present a set of three slides that show a model that clearly indicates how the positive ions pack in these "tetrahedral" holes. I then ask them if they want to change their minds. The majority do.

The net result: in one small component of my course, I have made a major improvement in the quality of the understanding that students take from the course. Every semester that I listen to students, I learn new things about how to change the way I "teach" the material I am presenting.

### How Organization of Topics Influences Learning

Almost 30 years ago, David Ausubel (*11*) proposed a general rule that can be summarized as follows: The best way to organize information after it is understood is not always the best way to organize it so that it will be understood in the first place. The organization of our courses seem logical to us, because we understand the material. But that doesn't mean our courses are organized in the optimum psychological order for someone encountering the material for the first time. We know what will happen to students later in the course, or in future courses. They have a hard enough time remembering what was done to them previously.

Because of your familiarity with the content of general chemistry courses, it may be impossible for me to convince you that this phenomenon occurs in this course. Let me therefore use a typical sophomore organic course as my example. The first semester starts with alkanes, and discusses alkyl bromides, alcohols, alkenes, alkynes, and concludes with aromatic compounds. The second semester than focuses on the chemistry of carbonyl compounds.

What implication does this have for the way the mechanisms of organic reactions are taught? The concept of nucleophilic attack—which is fundamental to so much organic chemistry—is introduced by examining what happens when a base, such as the $OCH_3^-$ ion, attacks an alkyl halide, such as $(CH_3)_3CBr$. In order to make sense of the chemistry of this reaction, the following factors must all be considered simultaneously: substitution reactions that lead to an alcohol versus elimination reactions that produce an alkene; $S_N1$ versus $S_N2$ mechanisms; $E_1$ versus $E_2$ mechanisms; 1° versus 2° versus 3° substrates; rearrangements of carbocation intermediates; and the effect of solvent (polar versus nonpolar and protic versus aprotic). Furthermore, the focus of this discussion is a class of compounds that have no intrinsic interest to anyone other than an organic chemist. Although the sequence of topics in the typical organic course is perfectly logical, it has the effect of forcing students to start the process of learning organic chemistry with what might be the worst possible system. (Those who enjoy conspiracy theories would have a field day with this.)

There are a few general rules for determining the optimum psychological order for presentation of material. First, and foremost, start with a topic that is closest to the students' experience. Second, build from their experiences toward more abstract notions when the student senses a need for some way to explain what he or she has already observed. Third, remember that no one learns from the generic to the specific. No one, for example, builds a generic equation such as:

$$Nuc:^- + R\text{–}X \rightarrow Nuc\text{–}R + X^-$$

before they construct an understanding of a specific example, such as:

$$OH^- + CH_3Br \rightarrow CH_3OH + Br^-$$

Finally, start with systems that have relatively few parameters and work toward more complex systems. If these basic rules were applied to a typical general chemistry course, I believe that there would be a significant change in the sequence of topics.

## Conclusion

The goal of this paper was to provoke a discussion of the following points

1. Reform of the general chemistry curriculum is necessary. (It might even be described as long overdue.) But this alone will not bring about a meaningful change in science education. We also need to change the way the curriculum is delivered.
2. Both theory and experiment decry the present reliance on lectures as the means of "teaching chemistry" at the college and university level. It might even be time to try some of the techniques our colleagues in elementary and secondary schools have developed to get around the fact that lectures have been historically shown to be the least effective way of building conceptual knowledge.
3. The present curriculum, coupled with the mode of presentation that characterizes most large general chemistry courses, often leads to knowledge without understanding.
4. The present structure of general chemistry courses produces a system of knowledge that students cannot apply to the world in which they live.
5. So much time is spent in general chemistry courses building the basic "nuts and bolts" that students need to master that we often forget to show our students why these are important skills.
6. So much attention is paid to individual skills that students never see an overview of how the topics come together.
7. There is a difference between teaching and learning.
8. The classical mode of teaching general chemistry focuses on the teacher, not the students.
9. Learning is best facilitated when the focus is on the students who are doing the learning, not the teacher.
10. There is evidence to suggest that less is more. That covering less material, but doing it well, may produce better students.
11. Learning is facilitated when the instructor spends less time talking, and more time listening to what students say.
12. The classic mode of instruction often consists of providing students with answers to questions they don't understand.
13. Alternative modes of instruction are possible, even in classrooms that contain 400 or more students at a time.
14. The sequence of topics that makes sense to us is not necessarily the sequence of topics that will produce the optimum learning in an individual encountering a course for the first time.

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