Award Address

You Can't Get There from Here[1]

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The title for this paper came from a book by Ogden Nash *(1)*, and many other authors have used it since Nash. However, it is also attributed to an old-timer sitting by the roadside who was asked by some tourists how to get to somewhere. His reply was, "You can't get there from here". He knew that the road ahead was a dead end and that the travelers had to turn around and take a new direction. I feel very like this man as I look out on the chemical education scene. Many of the problems we identified in the 1970s are still there despite 40 years of research. This should be telling us something about the direction we are taking and the need for change.

Setting the Scene

In 1971, my own group isolated chemistry topics that were causing problems for students in high school and that were not disappearing as students progressed to college and university *(2)* (see Figure 1). "I can't understand" became "I shall never understand" and eventually "I don't care if I ever understand". Inevitably, this led to the fall out from first-year courses that we all deplore. Many readers will be nodding their heads and saying, "I recognize these difficulties with my students". How did we get into this situation of thrusting these ideas on uncomprehending students for over 40 years and yet not see the stupidity of it all?

Let me tell you a monkey story. Animal behavior researchers placed a stepladder in a room with a bunch of bananas on top of it. Five monkeys were introduced into the room and one instantly went up the ladder to get the fruit. The others were "punished" by being hosed with cold water. The monkey who scaled the ladder was beaten up by the others. Trials continued for some time until they all got the message and the bananas were left untouched. One monkey was removed and replaced by a new one, who immediately went for the bananas but was beaten up by the others despite the fact that the cold shower was no longer being applied. Eventually all the monkeys were replaced one by one and were beaten up by their peers if they attempted to get the fruit. The situation stabilized with five monkeys sitting in a room with no attempt to get the bananas. If the researchers had been able to ask the monkeys, "Why does none of you go for the bananas?" a monkey would likely have responded, "I don't know, but that is how things are done here".

Are we in a parallel scenario? Are we still persisting in making our students sick of chemistry because "that is how chemistry is done here"? Who set the scene? How did it all come about? The answer lies not with some malevolent group of people, but with a response made in the 1960s in the United States and throughout the Western world to combat the perceived threat of Russian scientific supremacy. ChemStudy and Chemical Bond Approach sprang up in the United States, Scottish Alternative Chemistry and Nuffield Chemistry appeared in the UK, and similar schemes were launched in Western Europe and in Australia and New Zealand. The old "preparations and properties" schemes were replaced by what we have today. When these programs were introduced in the early 1960s, some enthusiastically embraced them and others were more reactionary. The enthusiasts, including myself, set out to persuade others. We ran courses, wrote textbooks, produced support materials, and eventually carried the others along. The "monkeys" had been programmed! You are the successors of all of this change and our students are the victims.

The writers of these "new" approaches were well-meaning academics with high reputations as chemists, who gave of their time and energy to transform what was to be taught in high schools and to alter university courses to fit. We embraced the new because it was seen to be modern and emancipating, yet here lay the trap. We were already professional chemists who understood the chemistry and rejoiced to see unifying principles appearing on which to systemize our own knowledge. We assumed that our enthusiasm would transfer to our students and produce generations of young chemists who enjoyed the subject, who were confident in their learning, deep in their understanding, and eager to pursue a career in chemistry. Alas, this was not to be so. Nearly 50 years on, we are still seeing the disappointment and disillusionment among our students that we had hoped to avoid. Students are voting with their feet, leaving us disappointed and thrashing about trying to find means to stem the flow.

What went wrong? There has been no lack of good chemistry, of enthusiastic teaching, or of ingenious and well-produced support materials. There have been many excellent projects involving new presentations, new initiatives (including computer-supported learning), group work, and discussion material such as ChemCom. However, these do not seem to have significantly stemmed the drift of disaffected students out of chemistry. What may have been missing was an understanding of how students learn. Concepts were introduced that were inappropriate for the students' stage of learning. Ideas were clustered in indigestible bundles, and theoretical ideas were not linked to the reality of the students' lives. The principle of beginning where students were and leading them forward somehow got lost. Perhaps we have been busy changing the menu in the ship's restaurant while the ship has been sinking.

We have had 40 years and more of chemical education (chem ed) research, much of it local and parochial, but enough of that research has ventured into the psychology of how students learn to yield universally applicable guidelines for a general overhaul of what is taught in high schools and beyond. No longer do we have to depend on trial and error to improve the learning experience of students. Chemists require theories and models to inform their research and provide mental frameworks to aid interpretation of results. Without our own theories and

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Areas of Chemical Difficulty (1971)

- Stoichiometry and the mole
- Balancing equations
- Ion-electron equations
- Bonding
- Equilibrium
- Electrochemistry
- Reactions of carbonyl compounds
- Hydrolysis, condensation, and esters
- Radiochemistry

Figure 1. Chemistry topics that students find difficult, as assessed by the author in 1971.

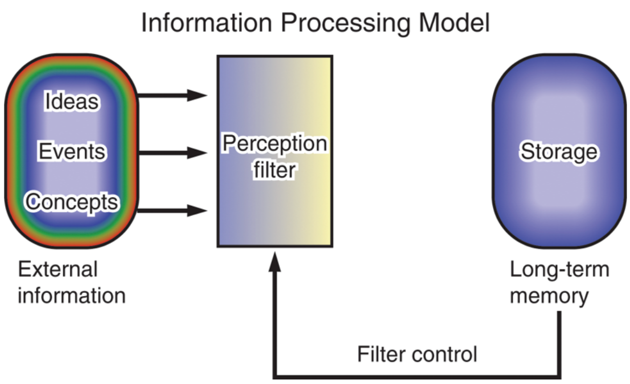

Figure 2. Schematic of author's model about learning that incorporates elements from Ausubel's theories *(6)*.

models chem ed will remain, in the eyes of the generality of chemists, a dilettante waste of time to be indulged in by people who cannot do "real" chemistry.

Models and Theories

My own research has led me to accept, develop, and use a model based on information processing. This model has appeared often in my publications *(3–5)*. It is in a simple form which any teacher can use as a rule of thumb in everyday teaching, although much more complex versions of it appear in the psychological literature. It also embraces most of the theoretical stances that appear in the literature. We, as researchers, need to merge and simplify our apparently disparate positions to give us one usable model applicable in the classroom. Too long have we suffered claims such as, "I am a Piagetian", "I am a constructivist", "I am an Ausubelian", or "I am an information processor". We are all trying to describe and understand the same subject: the human learner. We must find overlap despite our chosen stances. I am going to build up in stages the model I use and show how other models find a place within it (see Figure 2).

The principal tenet of Ausubel's work *(6)* is that what we already know (or think we know and understand), our interests, our prejudices, and our beliefs together control how we handle new information. This affects what we select from the sensory stimuli around us, how we process the stimuli, and how we store information. In effect, we each have a unique filter by which we individually select what interests us, what makes sense to us, and what is important to us. Very likely, one reader will select messages from this paper that differ from what another reader will take, depending upon previous knowledge, interests, prejudices, and beliefs. Herein lies the problem of teaching: information cannot be transferred intact from a teacher to a learner. The only way a teacher can be reasonably sure that a student has received and understood exactly what was intended is for teacher and student to discuss and exchange the understanding face to face. (Writers forego this luxury.) This is what Piaget said and also what alternative framework advocates believe. Ausubel made much of the differences in how learners store ideas in long-term memory—ranging from well-attached and integrated knowledge and understanding to stand-alone, rote-learned material. The former is easily retrievable while the latter is easily lost. Does this not agree with the constructivists and with Piaget?

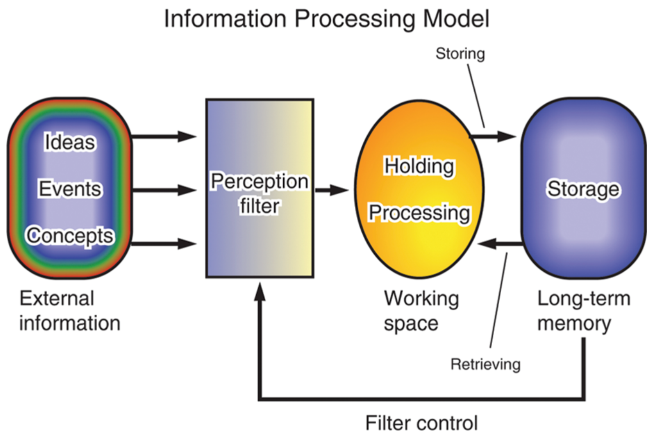

Figure 3. Schematic of author's model about learning that incorporates elements from Piaget's (and Piaget's students') theories *(7)*.

Adding working memory (working space) to the model in Figure 3, we can see where Piaget's stages fit in. Piaget's own disciples, such as Pascaul-Leone, Case, and Scardamalia *(7)*, were looking for a mechanism rather than a descriptor for the intellectual stages presented by their mentor; they proposed a working memory space that grew with age and reached a maximum at about the age of 16. Baddeley *(8)* extended and developed this work in helpful and practical ways, which resulted in the idea of a limited working space in which conscious thought takes place, bringing together new information admitted through the filter and information retrieved from long-term memory. There they interacted, looking for linkages between old and new knowledge (i.e., making sense of the new) and getting prepared for storage in long-term memory. Sometimes the linkages are faulty and give rise to alternative frameworks; sometimes no linkages could be made (i.e., no understanding was achieved) and the information was rejected or rote learned.

However, this working space has two functions: to hold information temporarily and to process it. It is a shared space. If much information has to be held, little room remains for processing. Conversely, if a lot of processing is to be done, little information can be held. Because the working space expands with age, more holding and processing can be done. The size of

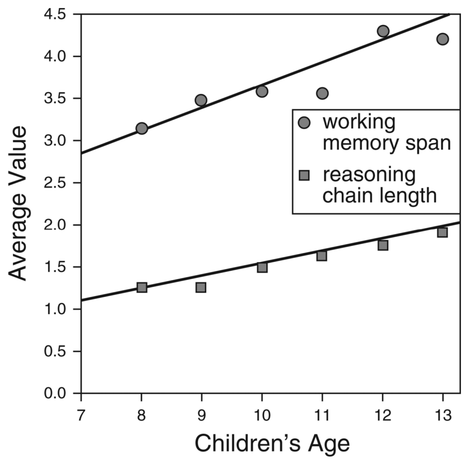

Figure 4. Comparison of children's working memory spans (capacity to store information temporarily and process it) and reasoning chain lengths (capacity to reason through multiple steps).

the working space reaches a maximum about the age of 16 and remains fixed thereafter. It seems that it cannot expand beyond that limit, but that we can learn to use it more efficiently in topics that interest us, and in which we have some expertise, while still being limited in less interesting areas.

An experiment *(9)* conducted with children up to the age of 13 shows the close relationship between working memory space and the ability to sustain a chain of reasoning containing multiple steps of the "if-so-therefore" kind. Figure 4 shows a connection between expanding working memory space and increasing number of steps in the reasoning chains with age. Piaget fits well into an information processing model.

The points on these two roughly parallel lines are average values for a sample of 50 children and show reasoning chain length about two steps less than expanding working space capacity. This difference is attributed to the space needed for holding and processing.

Before we leave this model, I must point out some potential misunderstandings that the reader might have. I have frequently seen, in papers, a misquotation of the work of Miller *(10)* and claims being made that the working memory space can hold seven plus or minus two pieces of information. This is only true if no processing is required. Remember, working memory space is shared between holding and processing. Such a situation would exist only when someone was asked to memorize a string of numbers and then regurgitate them without any processing being applied to them. However, if the subject was asked to hold a string of numbers and then give them back in reverse order, the apparent capacity measurement would be less than seven plus or minus two. To work at the limit of our capacity is usually uncomfortable, and we tend to work well below our potential. The more usual experimental values are nearer five plus or minus two.

Having now set up this model and shown that it embraces a variety of psychological stances, I will illustrate how it might help us to rationalize the problems students have with learning chemistry and indicate ways to remove the learning obstacles. No one model can encapsulate the complexity of human learning, but this one has proved to be useful in planning and interpreting the results of our research. It is basically a cognitive model that acknowledges the importance of the affective factors in learning.

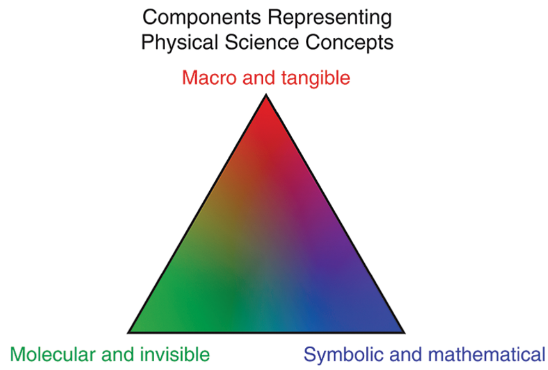

Figure 5. Three aspects of representation in the physical sciences.

Problems and Solutions

The list of topics that I have set out in Figure 1 became a starting point for a clutch of parallel research projects *(3)*. I allocated each topic to a researcher with the intention of looking for underlying causes and common factors for student incomprehension. In every case, the common factor that emerged was this: the quantity of information that needs to be manipulated as an individual learns and uses each of these topics was much larger than was at first anticipated. At this time we had not yet begun to have a model in mind, but these results drove us toward the model I have discussed above, illustrated in Figure 3.

Even the "simplest" mole calculations require more than five manipulation steps for a novice. When we used to do "normality" calculations, the problem could be reduced to a simple algorithm, $V_1N_1 = V_2N_2$ and could be easily solved, but by introducing molar calculations in the post-1960 curricula the complexity increased, leaving many students intellectually stranded. There were similar problems with ion-electron equations adding the complexity of symbol, state, charge, balance, product, and "spectator ions". Small things, but they are not small to a beginner!

One major source of overload of working memory lay in the very nature of chemistry itself. Figure 5 shows a triangle I have used to represent the three ways we look at chemical phenomena *(11)*. I borrowed this diagram from geologists who use such diagrams to represent the proportions of components in a family of minerals. Pure silica would be at one corner, alumina at another, and magnesia at the third. Any aluminum silicate would be represented along the side between the two components and the same would apply for any magnesium silicate. However, the composition of an aluminum magnesium silicate would be represented by a point within the triangle depending upon the contribution of each component.

Figure 5 has three components—macro and tangible; molecular and invisible; symbolic and mathematical—the three ways we look at or represent chemistry and its chemical changes. There is no hierarchy implied in this model, and any additions to it are superfluous and complicating. Let us keep things simple or the model will not be used.

In a chemistry lesson, a teacher may flit from corner to corner of the triangle. Holding up a test tube of a blue solution the teacher may say, "I have here an aqueous solution of a copper salt. The blue is due to the hydration of the copper ions, written as $Cu^{2+}(aq)$." In the same breath the teacher has touched all three corners of the triangle and has in fact gone into the center of the triangle. There is no guarantee that any student has followed the teacher. This is a very simple example; consider a slightly more complex one in which a solution of copper chloride is being electrolyzed between a pair of carbon electrodes. Someone making a macro observation sees a brown layer forming at the cathode, bubbles forming at the anode, and a slow fading of the blue color. Readers are invited to enumerate all the extra pieces of information (ions, charges, migration, discharge, and so on) and the representation that will be needed to interpret this experiment. I can find nine in total! Overload of working memory? It is so easy for the teacher to flit about the triangle, but what about the learner?

If we glance once more at the problematic topics in Figure 1 and think about them in this analytical way, the source of the difficulties will become evident. Figure 5's triangle is a useful tool for estimating the load being placed on the working memory.

Thinking the Unthinkable

So much of what we teach is accepted as fundamental and immutable (the monkeys again), and yet we know that many of our students are just not getting the message. Any experienced teacher knows the frustration of seeing, in exam answers, evidence of incomprehension despite our best efforts, and yet we go on perpetuating the situation because "that is the way chemistry is". It is about time that we thought the unthinkable and questioned our acceptance of the situation. If 40 years of research and ingenuity have not found a "cure", something else must be done.

Some chemistry content will have to be removed from the high school curriculum, some topics will have to be reduced, and some topics will have to be rescheduled to fit what we now know about learning. The starting points and emphasis in teaching chemistry must also change.

Adopting a Rational Approach

Let us go back to the model in Figure 3 and use it to help us to think through possible strategies to provide a rational basis for such a revision. Begin with the idea of the filter that is driven by what the learners already know and by what interests them. There is no point in beginning a course in chemistry with a treatment of atomic electronic configuration or bonding because the anchorages in long-term memory are not there. Without attachments in long-term memory, a student can only learn by rote methods. An approach to chemistry through acids, bases, and salts is unlikely to stir students with enthusiasm. Apart from common table salt, how many salts are in place in long-term memory to provide relevance and reality for the learner? On the face of it, inorganic compounds are "simple", but are they? So many wrong concepts are introduced by teachers or constructed by the learners in this area of chemistry. A glance at a book of chemical data will show the absurdity of suggesting that sodium (or any other metal) is "anxious" to lose electrons and chlorine is "desperate" to accept them. It is too soon to introduce lattice energy or hydration energy to provide a rational basis for compound formation. The octet rule, with all its pitfalls for later study, tends to raise its ugly head here as a sort of rationalization.

The model suggests that we should begin where students are, with their interests and experience, and lead them into discovering new ideas among the familiar. An obvious starting point is in organic chemistry, with gasoline, camping gas, food, clothing, plastics, and drinks and so much more that is familiar. I know that it has been the tradition to keep organic for later, but are we taking a "monkey" point of view? Let us consider some of the advantages in starting here.

The long-term memory already contains anchorages for what we want to teach and the filter is primed and ready to go. The working memory is not in danger of overload. We can go a long way into organic chemistry with only a few elements: carbon, hydrogen, oxygen, nitrogen, and possibly sulfur and phosphorus. Most of these are familiar (at least their names are) to the learner. By considering the spatial arrangement of the four electrons around a carbon, students, using their fingers, can see that a tetrahedral arrangement is likely. Never mind sp^3 hybridization. It is a cobbling together of atomic orbitals (isolated atoms in the gas state) to produce a tetrahedron. This is using unreality to arrive at reality. Pasteur knew about the tetrahedral arrangement long before atomic orbitals were conceived.

Using the simple tetrahedral idea, we can do a lot of sound organic chemistry linked to what the students already know, avoiding overload of working memory. Only when we reach organic acids do we have to reconsider bonding, but this can now be linked to the simpler ideas of covalent bonding already established. Another advantage of beginning with organic is that there is no pressure to use balanced equations. Practicing organic chemists do not bother, so why should we?

The model has led us to select a starting point that fits what is already in a student's long-term memory. The working memory is not overloaded because only a few elements are involved in making familiar compounds. The representation triangle can be used along its sides to build ideas of the relationship between the macro and familiar, with the molecular. The use of the representational is reduced, and no calculations are necessary. All of this provides a logical basis for an applications-led approach instead of a conceptual approach followed by a passing mention of uses and applications.

The troublesome mole can be rethought in the light of the model. It has been my sad experience to have graduate students who confessed their inability to do mole calculations. The very word "mole" left them uncomfortable. How could highly intelligent young people have such an aversion? They met the mole too soon, wrapped up in incomprehensible (and even totally irrelevant) calculations that flooded the working memory into a state of paralysis. In an earlier publication *(4)* I set out an analysis of a trivial (from my point of view) mole calculation. I saw it as a four-step procedure, which did not tax my working memory, because I already had tricks for grouping the processes, but students saw it as a ten-step task, which blew their working memory.

So much of the problem has its origins with the definition of the mole. The mole is the amount of substance of a system that contains as many entities (atoms, molecules, ions, or other particles) as there are atoms in 0.012 kg of ^{12}C. I have no logical quarrel with it, but by its circuitous language and presentation it ranks alongside an old puzzle, namely: A man is looking at a photograph and says: "Sisters and brothers have I none, but that man's father is my father's son". Whose picture is he looking at? This is good for an argument any time!

What is so wrong with introducing the mole as a number? I can hear the purists squawking. The concept can be "upgraded"

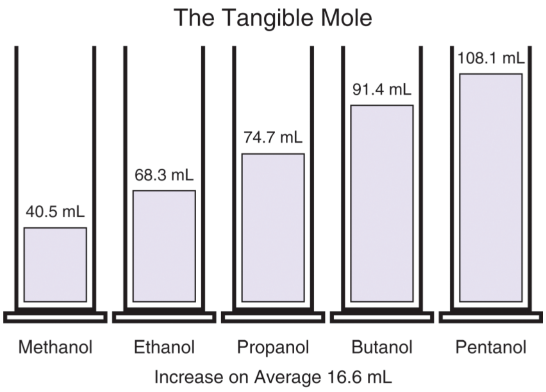

Figure 6. Comparison of molar volumes of an homologous series of alcohols.

later when the learners are more sophisticated. Think how it could illuminate areas of chemistry and make the linkage between macroscopic and submicroscopic easier. While doing organic chemistry, the mole could provide insights about a homologous series, as in Figure 6.

This example is not new and appeared in textbooks in the 1970s *(12)*. Has it been forgotten or has the definition killed it? Students can "see" the relative sizes of the members of the series and "see" the increasing chain length because each tube contains the same number of molecules. This applies to other homologous series of liquid compounds.

Moles of sugars can be weighed out and placed in tubes of the same internal diameter. Which are monosaccharides and which are disaccharides becomes evident because one column is about twice the height of the other. It is instructive for students to see a 20-L solvent drum alongside a test tube containing 18 mL of water, to get some idea of spacing between molecules in the gas phase. The mole treated this way is a natural bridge between macroscopic and submicroscopic. In these cases, the mole is treated as an extensive property, like mass. The problems begin when a mole is dissolved in a solvent and we get molarity, an intensive property, like density. Intensive properties are notoriously more difficult for students to grasp than extensive ones are. Working on the principle that students should encounter and master simpler concepts first, there may be a case for postponing the introduction of moles in solution until much later and even then they might occupy a much smaller part of the curriculum. Apart from analysts, most chemists use moles at a very low level, well below the complexity typically demanded of students. In the 19th century, many academic chemists in the United States were Scots, or the students of Scots, who had come from a background of industrial analysis and quality control. The whole concept of "normality" originated in Glasgow to establish standard concentrations for industrial chemicals. It is little wonder that they took this with them to the United States and the laboratories they set up were highly biased toward analysis. This certainly persisted in university laboratories in Scotland until the 1970s.

Perhaps we are living with a hangover from these days and cannot imagine laboratories without burets. Eliminating quantitative analysis may offend some readers, but it is worth at least reconsidering its place in high schools and even in first-year courses. Special analytical techniques are largely instrumental and can be taught later at university level.

Equilibrium Confusion

Physics	Chemistry
Masses or moments are the same on both sides	Masses or moles need not be the same on both sides
Adding to one side makes the balance tip to that side	Adding reactants "tilts" towards products
A balance has sides	There are no "sides"
You can do something to one side only	Changes of *T* or *P* affect both "sides"
Static	Dynamic

Figure 7. Comparison of equilibrium in physics and chemistry, illustrating potential sources of chemistry students' confusion.

Concepts and Language

The vast bulk of our teaching and learning is done through the medium of language. Language, lodged in long-term memory, takes part in the thinking processes in working memory and plays a major part in filtering incoming information. When language is particularly unfamiliar it takes up space in the working memory. Storage problems in long-term memory are created when a familiar word changes its meaning in another area of science, leading to misfiling and to the formation of alternative frameworks, the personal interpretations of what is heard or read.

The most susceptible topic to this misfiling is the concept of equilibrium. Students who meet physics before chemistry have laid down a set of concepts and language that accords with everyday experience and can be illustrated with nothing smaller than a building brick. Now comes the chemistry class with talk of equilibrium, using the same language as the physicist, but the concept is now entirely counterintuitive. Figure 7 summarizes the two distinctly different concepts. I frequently read papers lamenting the inability of students to handle the equilibrium concept, particularly in calculations. When one adds to the language—and the associated intuitive physics concepts—the overlay of calculation, it is little wonder that chaos reigns. For most purposes, it is enough to establish the nature of chemical equilibrium without the added burden of fatuously complex calculations.

In reality, industries do not do their business with reactions arriving at equilibrium; rather, they are driven by kinetic considerations. The Haber ammonia process, much quoted in textbooks, is never carried out under equilibrium conditions but recycled to meet kinetic criteria. In biological systems, situations like buffers operate in a "simple" equilibrium manner, but in most situations we find secular equilibria, where one reaction depends upon the production of products from a series of previous reactions and the products in turn control the next reaction on a complex chain. Perhaps we give too much attention to "simple" equilibria at the expense of the secular. Such equilibria also exist in radioactive decay series.

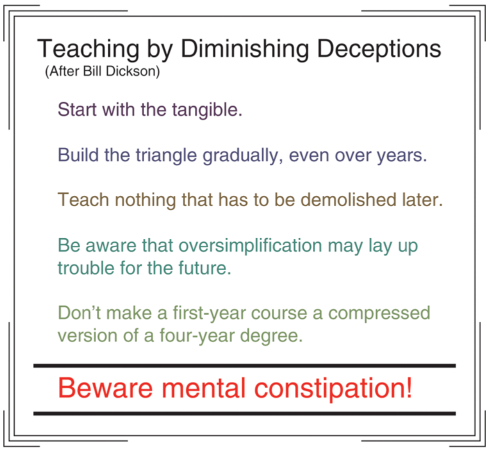

Figure 8. Principles for teaching chemistry—or anything else!—effectively.

One might be cynical and suggest that the emphasis put on calculations, in general, is to provide easily set and easily scored exam questions. Being able to do the calculations does not guarantee that the student understands the underlying concepts, as so many research papers have shown. My first boss, Bill Dickson, used to tell me that the best way to teach chemistry was by a series of "diminishing deceptions". In my youthful enthusiasm, I did not fully appreciate his advice. Now older and wiser, I can see that it makes sense, and I apply it in Figure 8.

I have tried, within the confines of a brief paper, to set out a rationale for the changes we need "to get there from here". We need to rethink a lot of what we teach. This does not imply that we have been teaching bad chemistry, but rather that we have been teaching inappropriate chemistry at the wrong time and in the wrong way. We have been presenting chemistry in a way contrary to what we now know and understand about learning. What I am proposing is definitely not a dilution of chemistry, not a dropping of standards, but a tailoring of the subject to meet the psychological needs of learners. In the process we may decide that some things we teach are past their "sell-by date". They have served a useful part in the evolution of the subject, but are no longer necessary for the understanding of the subject as it has now evolved. Let us reexamine topics like the phase rule, closed system thermodynamics (because most undergraduate chemistry is conducted in open vessels under constant pressure conditions: in test tubes, flasks, and condensers), Carnot cycles, colligative properties, and wave mechanics to mention but a few. Something has to go to allow for the consideration of so much that is new. This does not imply that these topics are wrong or unworthy of a place in the scheme of things, but that they may be inappropriate for high schools and undergraduate courses. They may find their place at the specialist graduate level when students need courses as part of their preparation for some research line. Many readers might be offended by these ideas because they imagine that I am demeaning some part of the subject that they enjoy and find fulfilling. On the contrary, I am trying to find some logic in the way we present the subject so that students will learn efficiently, with understanding and enjoyment. We can get there from here, where at present, students are frustrated and leaving us.

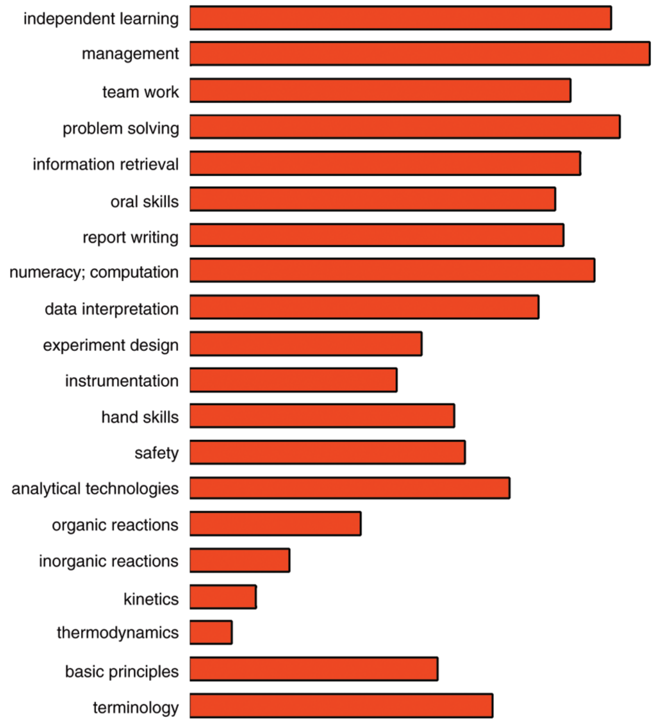

Figure 9. Relative comparison of the skills respondents reported were required in their chemistry workplaces (see ref *14*).

Finally I would like to tell you about some work in a preliminary stage in the UK and invite the ACS (and whosoever will) to join in. The purpose of this work is 2-fold:

- To gather together a digest of 40 years of Chem Ed research and set out its clear messages for the chemistry community about the areas of the subject needing care and attention.
- To find out from practicing chemists what they need from university courses to prepare them to be efficient, well-rounded, well-educated chemists in the real world, capable of applying their skills for the solution of many of the problems besetting the world at present.

I should like to give you a glimpse of some very preliminary findings that have emerged. By trawling through 36 international journals of science education *(13)*, researchers have distilled that—surprise, surprise—the problems are the same as those set out in the 1971 list at the beginning of this paper! A wider search may be necessary, but I fear the results will be similar.

The pilot study conducted on graduates from three universities to ascertain their views about the chemistry courses they took and those courses' utility in the graduates' employment has yielded very interesting results *(14)*. About one hundred graduates were involved in the survey, and they are now employed in chemical industries, chemistry teaching at high school, or as graduate researchers. The three groups were roughly equal in number. They were asked questions by interview and questionnaire. One question asked them to enumerate the skills that they had been obliged to use during their career so far. The results are shown in Figure 9.

It may surprise readers to see the predominant skills required of these graduates and also those that scarcely featured at all. Another supplementary question asked for the frequency

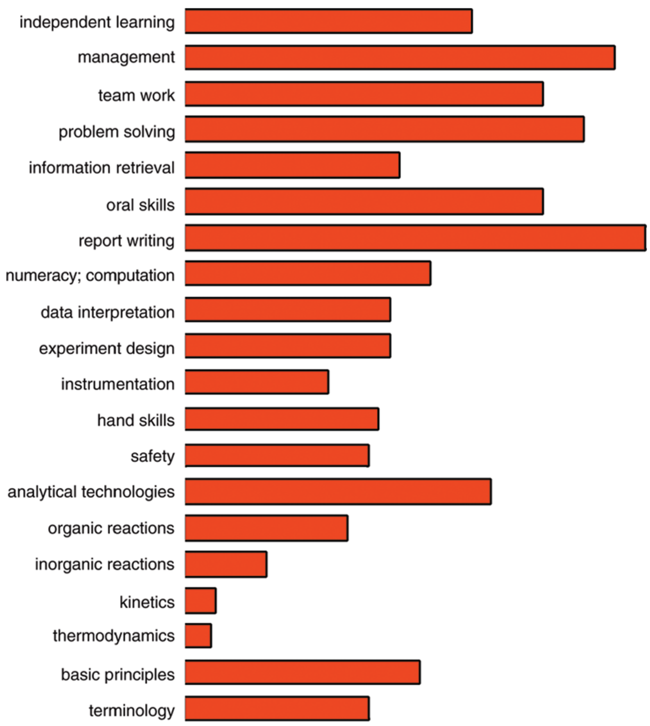

Figure 10. Relative frequency of these skills' use in the respondents' chemistry workplaces (see ref *14*).

of the requirement to use these skills. The results are shown in Figure 10.

The response to this question accentuates the need for process skills and reduces the call for specific chemical skills. However, the respondents clearly stated, in response to another question, that they did not want a less demanding or less rigorous chemistry university course; rather, they felt that too little had been done to prepare them with the process skills being required of them. There was a suggestion that it should be possible to learn and exercise these skills through the medium of chemistry. I have said quite a lot about the content of preparatory chemistry, but it would be timely to reexamine the presentation and methodology of chemistry at all levels. Various attempts have been made to introduce discussion and presentation methods for dealing with environmental and economic aspects, notably *Chemistry in Context (15)* and Salter's Chemistry *(16)*, backed up by research in Glasgow over a long period *(17, 18)*. The real challenge will be to incorporate such methods into the mainstream teaching and learning of chemistry. As I indicated earlier, we can only be really sure that students have grasped what we have taught when they can explain their understanding to us in some face-to-face situation. The formal lecture does not allow for this interaction and examination by multiple choice or other fixed-response methods cannot fully probe understanding *(19)*. Students cannot display their misunderstandings if they are presented only with wrong responses that we think they may have in mind.

Action

So where do we go from here? There is an immediate need for a total reexamination of what is taught in high schools in light of the models presented in this paper so that students are not put off chemistry early. Decisions about careers are forming as early as 14 years of age *(20)*. Chemistry should be presented in a way that capitalizes on what students are familiar with and for which they already have anchorages in long-term memory. This might require a complete reordering of what is taught, with the possibility of an applications-led structure to maintain interest, beginning with organic chemistry. Some content may have to go; some might have to be postponed even for years, and some rescheduled. Nothing should be so sacrosanct as to escape this scrutiny. Concepts must be built from the macroscopic and gradually be enriched with submicroscopic and representational aspects.

At the undergraduate level, content should undergo the same scrutiny as suggested above. Some topics may have to be rethought so that first-year students are not subjected to what amounts to a compressed and indigestible four-year course. Some topics may be "mothballed" and be used at some later specialist level or get an honorable place in the study of the evolution of chemistry.

Chemistry should be considered as an excellent vehicle on which to develop vital process skills. Because the problems exposed in this paper are functions of human learning, they are of interest and importance internationally. It should be possible to generate international cooperation among professional bodies such as the ACS, the Royal Society of Chemistry, the Royal Australian Chemical Institute, the International Union of Pure and Applied Chemistry, and similar bodies around the world to face up to and act upon the findings of 40 years of chemical education research. The combined power of these bodies could have a huge impact on the future learning of chemistry and indeed upon the very shape and existence of the subject for many years to come. There are surely academics of standing in the chemical community today who can see opportunities to reshape the future of education in chemistry and make it the central science that it could and should be.

Note

1. A. H. Johnstone, Emeritus Professor of Science Education at the University of Glasgow, Scotland, received the 2009 American Chemical Society Award for Achievement in Research for the Teaching and Learning of Chemistry on March 24, 2009, in Salt Lake City, UT. This paper is adapted from his award address.

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