

Award Address

Chemistry Teaching—Science or Alchemy?

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Introduction: Is Chem-Ed Research?

Many of us who work in universities have two main roles: as researcher and as teacher. The balance between these varies from one institution to the other, and the approach to these roles can be very different. Some people see

You may be the provider of stimuli during teaching, but how does the student filter what you provide?

teaching as a chore which gets in the way of research, while others view their teaching as an exciting, creative, but often frustrating pursuit. Journals such as this regularly carry articles describing some frontier of chemical research along with articles about teaching innovation. Where the two types of communication differ is in their overt theoretical

stance. The research papers are copiously referenced to theories, held beliefs, hypotheses, and objective measurement and seek to build on and extend what has been done before. The teaching papers, on the other hand, are full of assertions, homespun wisdom, and ingenuity, and lack measurement.

I am suggesting that the development of good teaching and the pursuit of research have (or should have) essentially the same structure. We need some discipline in our work to give it a clear focus, to be efficient in time and effort, and to have a direction that is more often right than wrong. We also need transferable outcomes that all can share, to prevent the constant reinvention of fire.

The bulk of this paper is an attempt to do the gathering together of things we have all been aware of, perhaps intuitively, and to provide a working model for new research and development in chemical education. It is an attempt to systematize what is known into a usable form, which might save us from confusing *our* enthusiasms for those of our students and which will help us to go with the learning process rather than across it or even against it!

The model draws upon the work of psychologists, educationists, artificial intelligence workers, and dealers in common sense.

Constructing a Model of Learning

In common with all living things, we are victims of our environment, informed by our senses and reactions. However, we have mechanisms by which we reduce the torrent of sensory stimuli to manageable proportions, attending to what seems to be important, interesting, or sensational. In

other words, we have a filtration system that enables us to ignore a large part of sensory information and focus upon what we consider to matter. To try to attend to everything would be an impossibility leading to confusion and breakdown.

We then have to ask how the filter works. It must be driven by what we already know and understand. Our previous knowledge, biases, prejudices, preferences, likes and dislikes, and beliefs must all play a part. How else would we anticipate and recognize the familiar or be caught out by a surprise?

Although in any one country or culture much of this will be held in common, each individual will have a unique set of held knowledge and beliefs that mark us out as separate people and personalities.

Not only do we sense selectively, we also add, from experience, to our sensory information and “fill out” an otherwise incomplete sensory experience. Take a look at Figure 1. Is it just a lot of meaningless blots? Try turning the page upside down. What now? The image is poor, but its meaning is clearly being supplemented by what you already know and “filled out” to a meaningful thing.

Somewhere in our heads is a vast store of experience and knowledge, one function of which is to activate and control our perceptual filter. Stop and give some thought to the implication of this for teaching and learning. You may be the provider of stimuli during teaching, but how does the student filter what you provide? If essential previous knowledge or concepts or language is missing, how will this affect what your students take out of what you say? Will they miss essentials and grasp peripherals? Will they remember the bangs and pops of a demonstration and totally fail to grasp what you were trying to teach? Will your clever graphics, trying to convey a three-dimensional structure on a flat computer screen, fail because the students are not familiar with drawing conventions or are incapable of generating three dimensions mentally from two-dimensional stimuli or even of seeing “near” things far away and vice versa (1)?



Figure 1. Meaningless blots? Turn the page upside down and look again.

Let us move deeper into the model by considering what happens to the stimuli and information we admit through the filter. It is thought to pass into a *working space* (or *working memory*) where it is held and manipulated before being rejected or passed on for storage. This part of the processing train has been thoroughly researched by workers such as Baddeley (2) and has given rise to a much more complex model than I am presenting here. Readers might want to pursue this further, but a simplified version will suffice for the present purpose.

The working space has two main functions. It is the conscious part of the mind that is holding ideas and facts while it thinks about them. It is a shared holding and thinking space where new information coming through the filter consciously interacts with itself and with information drawn from *long-term memory store* in order to "make sense" (Fig. 2).

However, there is a drawback. This working space is of limited capacity and I have written about this before in this *Journal* (3). It is a limited shared space in which there is a tradeoff between what has to

be held in conscious memory and the processing activities required to handle it, transform it, manipulate it, and get it ready for storage in long-term memory store. If there is too much to hold, there is not enough space for processing; if a lot of processing is required, we cannot store much.

It is easy to show this experimentally. Before you read further, get two pieces of paper or card and cover the right column of Table 1 and all of the left column except the first line. Here is an experiment you can try on yourself. The table shows a date in words, "Seventeenth of March". Do this *entirely in your head* (no writing). Convert the date to numbers and arrange them in numerical order from the smallest to the largest. Step one, memorize words and look away. Step two, translate to numbers 1, 7, 3. Step three, rearrange numerically 1, 3, 7. That was easy! Now uncover the next date for 2–3 seconds, cover it, and repeat the processes above. Check your answer in the right column. Work your way down column one until your "brain begins to hurt".

Table 1. An Experiment

SEVENTEENTH MARCH	137
TWENTY-THIRD OCTOBER	0123
FIFTEENTH APRIL EIGHTY-NINE	14589
TWENTY-SIXTH SEPTEMBER	1267899
NINETEEN EIGHTY-SEVEN	
NINETEENTH DECEMBER	11122489
EIGHTEEN TWENTY-FOUR	

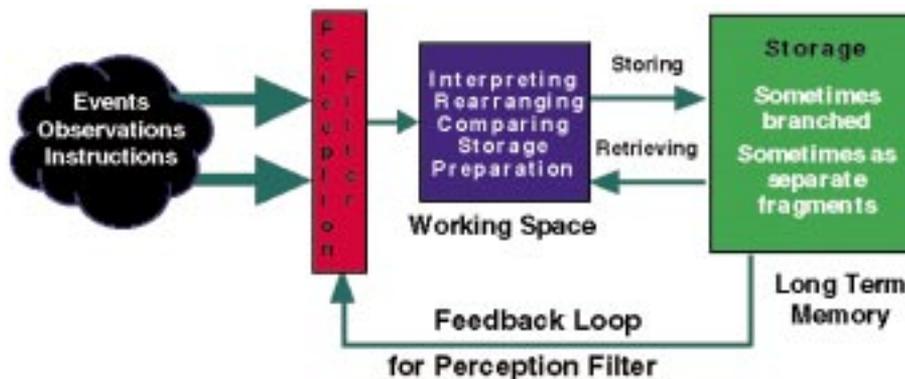


Figure 2. Information processing model.

There is a cutoff at the point where the effort of holding in memory conflicts with the two thinking processes of translating and rearranging. The shared space is overloaded. In practice, it is so uncomfortable to work up to the limit that we operate below it, thus limiting the working space even further. How well did you do in the experiment?

What are the implications of this for learning? Not only do students filter what we give them, but there is a limit on the quantity they can process and this also has a time factor included. Does this mean that we are "crippled" by this mental limitation or can we expand the working space? The evidence is that we cannot expand the space, but we can learn to use it more efficiently. A simple example is seen when children are learning to read. At first every letter is a

piece of information that has to be processed into words and then into a sentence. To begin with, H-O-R-S-E is five pieces of information, but soon the child rolls this together into one word HORSE (one piece of information). In its first form, the name is occupying five bits of space

but later it uses only one bit of space. Later whole sentences can coalesce to one space, or at least the sense or message of the sentence takes only one space. This process is called chunking and it is this that enables us to use the limited working space efficiently. However, chunking usually depends upon some recognizable conceptual framework that enables us to draw on old, or systematize new, material. For an experienced chemist, the recognition that ligands, bases, and nucleophiles are related provides a helpful chunking device. Unfortunately new learners do not have these chunking devices in place and so are severely limited by their working space until they grow the concepts for themselves. This can be seen experimentally in the data in Figure 3.

The data were provided by the Scottish Examination Board on questions they had set on the mole. The sample size was 22,000 sixteen-year-olds. The vertical axis is the fraction of the student sample solving each question correctly. The horizontal axis is the sum of the pieces of information provided in each question plus the additional pieces to be recalled plus the processing steps required. For each question, this total was agreed upon by a jury of teachers and then checked by getting a group of students to solve the problems out loud. The data for each question were then plotted against the two axes.

As one would expect, as the complexity increased the performance fell, but not linearly! Figure 3 shows the curve of best fit, which looks very like a pH curve. It is the kind of curve that fits any phenomenon in which a change of one condition seems to affect the other very little until there is a sudden and drastic change. Here we see students having

success with a cluster of questions of increasing complexity until a point is reached after which most students fail. It comes somewhere between five and six pieces of information and operations. Check back to the experiment you did on yourself with the dates. Was it somewhere near that point when you started to make mistakes?

In the mole exam questions, students began to fail when working space was overloaded. I am not sure that the working space capacity was what the exam was trying to measure! You will notice, however, that the curve does not drop to zero, because some students, about 10%, are showing signs of chunking and being able to handle the complexity. In this area, M-O-L-E has become MOLE for some.

So far the model (Fig. 2) has helped us to understand that idiosyncratic filtration takes place in the mind of each student, by which the things we are teaching are deemed to be important or unimportant, understandable or baffling, interesting or boring. All of this is controlled by what is already held in long-term store. It has also pointed out the limitations of working space in the information processing train. In both of these areas, learning can go wrong or not take place at all.

However, the model takes us on one step more to look at the linkages between working space and the long-term memory store. Look back to Figure 2 and you will see a double arrow indicating a constant coming and going between the two areas. Processed material in the working space is passed to the long-term memory store for safekeeping and at the same time material is being recalled from the long-term store to help with the processing in working space. These are the processes of memorization and recall upon which so much of our functioning depends.

There is the functional, knee-jerk kind of recall by which we react quickly to external stimuli and little conscious thought is required. Much of this has to do with physical skills such as walking, driving, or using a buret or a spectrophotometer (4). The other kind of recall has to do

with thought, which may be slow, concentrated, two-way between the working space and the long-term memory store and is what we like to believe takes place in academic thinking and learning and pervades problem solving.

What does the model indicate about storage and recall?

Storage and Recall

On a simple level one could compare storage and recall to a filing system in which new information is related to existing files and placed there. If an incoming letter does not fit the system, a new file is created and cross-referenced or indexed in some way to facilitate its retrieval. However, the problem arises at the retrieval stage because the operator has to understand the system and the logic of the original filing. It is very difficult to take over someone else's filing system and find things again. What is logical to one person may not be so logical to another.

This brings us to a group of major thoughts. The first is that humans are *pattern seekers*. We try to relate new things into an existing system to "make sense" of things. The discomfort of something which does not make sense, often leads to the rejection of the new idea.

The second major thought is that we *build our own knowledge* from what is presented to us. Learning is not the transfer of material from the head of the teacher to the head of the learner intact. Learning is the *reconstruction* of material, provided by the teacher, in the mind of the learner. It is an *idiosyncratic reconstruction* of what the learner understands, or thinks she understands of the new material provided, tempered by the existing knowledge, beliefs, biases, and misunderstandings in the mind of the learner.

Let us carry this thought further, and I am conscious of the fact that readers will take different things out of what I say. Storage can take place in at least four ways.

- *The new knowledge finds a good fit to existing knowledge and is merged to enrich the existing knowledge and understanding (correctly filed).*

- *The new knowledge seems to find a good fit (or at least a reasonable fit) with existing knowledge and is attached and stored, but this may, in fact, be a misfit (a misfiling).* These misfits often have a semantic origin. For example, students were given a lecture on dipole moments, permanent dipoles, and instant dipoles in molecules. At a later tutorial, the tutor was checking these definitions and found that students had linked synonymously instant dipoles with dipole moments. Further investigation showed that the confusion was arising between "instant" and "moment". "Are they not just the same?" asked the students! It was logical to them, but it was not what the lecturer intended. The reader will have encountered many examples of this in examination scripts when students come up with ideas and explanations we never taught them. These very useful revelations (from a diagnostic point of view) are often lost in multiple-choice questions where students have restricted response possibilities. What we use as distracters are often based on mislearning we assume they might have, rather than what they actually have.

- *Storage can often have a linear sequence built into it, and that may be the sequence in which things were taught.* Lecture 5 comes before lecture 6 and so the content of 6 is separated from 5 or 4 or 3. Students can only handle questions if they have the same sequence. The algorithmic type of problem solving has a linear sequence that students can

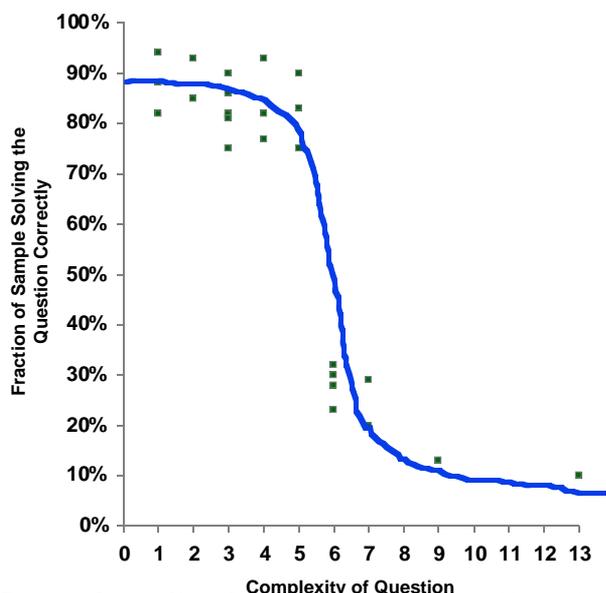


Figure 3. Curve of best fit. Students have success with a series of questions of increasing complexity until a certain point, after which most students fail.

relate to, but problems that break this are seen to be difficult or impossible. In normal life we have sets of linear memories that can be accessed in only one way. For example, to answer "What is the tenth letter in the alphabet?" involves going to A and counting through to J. "How many days are there in November?" will drive us to some jingle like "Thirty days hath September...". "In the first row of the transition elements, which one has a d^6 configuration?" will make us count from scandium, titanium, vanadium, etc. This type of memorization and retrieval is necessary, but often slow and awkward, needing a lot of effort. If the linearity can be broken down by spurs or branches, access becomes easier. The transition metal problem is reduced if we add to our chain the knowledge that manganese is the middle element in the sequence with a d^5 configuration. Students need help with laying down such knowledge.

• *The last type of memorization is that which occurs when the learner can find no connection on which to attach the new knowledge.* This is both hard to learn and almost impossible to retrieve. This is the kind of learning that necessitates walking up and down with a wet towel round the head and chanting things over and over again. Learning is painful and often a complete waste of time in that it is easily lost or consciously rejected. It is the learning crammed in before an examination that is lost within an hour or so after the test.

Ausubel (5) has grouped these types of learning between two ends of a spectrum. The first, described above, in which new learning links correctly to old knowledge and understanding, is called *meaningful learning*. The last type, mentioned above, is called *rote learning*. At one extreme we have good, well-integrated, branched, retrievable, and usable learning, while at the other extreme we have, at best, isolated and boxed learning that relates to nothing else in the mind of the learner. However, a sympathetic and skillful teacher, aware of the boxed learning, can help students to interconnect boxes and convert rote to meaningful learning. I can vividly recall one lecture on hard and soft acids and bases, which brought so much—apparently disparate—chemical knowledge together for me. If water is a hard base, hard acids must be the cations found in the sea. If I am to put a metal transplant into a human body, that metal must not yield hard acid ions in this aqueous medium or corrosion will set in. Hard bases tend to donate electrons through oxygen or nitrogen (top of periodic table), while soft bases donate through sulfur or phosphorus (lower in the table). Suddenly a lot of things came together when I realized that ligands were bases and so, often, were nucleophiles. This is meaningful learning! In this situation retrieval is easy because the cross-index system is now able to work along many channels. I believe that although learning is idiosyncratic and individual, students can be helped to learn by discussing with them the content of the last few pages of this article. Without such help, students can imagine that learning chemistry is a rote process and this may be exacerbated by the kind of testing we subject them to. This *shallow learning*, as described by workers such as Entwistle (6), can become a way of life for students who imagine that this is what chemistry is about. The interlinked, multidimensional learning we described at the beginning is close to what Entwistle describes as *deep learning*, but he adds the idea that this requires a commitment on the part of the student (and the teacher) to see this as a necessary and satisfying condition for learning. I believe that it is our responsibility

as teachers not only to purvey the chemistry but also to enable and encourage students to learn how to learn. How this might be done will be set out in the section below.

The Model in Action

I should like to devote the rest of this paper to the application of this model to real

teaching situations in chemistry to illustrate its usefulness and to give direction to our interests, enthusiasms, and research.

It is probably a good idea to summarize what has been said so far in the form of principles for teaching and learning. My research team call these the Ten Educational Commandments. They stem directly or indirectly from the model.

1. What you learn is controlled by what you already know and understand.
2. How you learn is controlled by how you have learned successfully in the past.
3. If learning is to be meaningful it has to link on to existing knowledge and skills enriching and extending both.
4. The amount of material to be processed in unit time is limited.
5. Feedback and reassurance are necessary for comfortable learning, and assessment should be humane.
6. Cognizance should be taken of learning styles and motivation.
7. Students should consolidate their learning by asking themselves about what is going on in their own heads.
8. There should be room for problem solving in its fullest sense to exercise and strengthen linkages.
9. There should be room to create, defend, try out, and hypothesize.
10. There should be opportunity given to teach (you don't really learn till you teach).

On the way through the applications that follow I shall refer back to these Ten Commandments and, through them, to the model.

The Model Applied to Lectures

In a three-year study during which we tried to see lectures through the eyes of students, we were assisted by seventy students who let us have their lecture notes at the end of a selection of lectures. We copied these and returned them to the students. We also attended each lecture, recorded it, and took a set of notes for ourselves. Our observations plus the analysis of the students' notes gave rise to the following findings.

The first was that most lecturers delivered about 5000 words per 50-minute lecture. The student response to these different lecturers was related to their lecturing style; their rate of delivery, their humor, their use of visual aids, and the vocabulary employed. However, the main factor was that of *cues*; how did they help students to separate noise

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from signal. Some lecturers were very clear about what was essential and what was peripheral, while others left the students to figure this out for themselves, with often disastrous consequences.

We found that students on average recorded between 500 and 1000 words; between 10% and 20% of what was said. But how did they select that fraction? Clearly previous knowledge would enable them to decide what was important and made sense, and what was unimportant (commandment 1). Their learning style was also important; whether they were visual or verbal learners and whether they could separate the essential from the peripheral (commandment 2).

One of the main ways of coping was for students to work on the assumption that if the lecturer went to the trouble of writing something on the blackboard, it must be important. Also the pace of writing on the blackboard was slow enough to match the students' recording pace. We analyzed the students' notes to see how complete the blackboard record was and found four categories: those who copied, but did so inaccurately or incompletely; those who copied the blackboard material only, but accurately; those who had a complete and accurate blackboard record but who also had noted a fair amount of the verbal communication; and finally those who had complete, accurate blackboard notes and also had elaborated them with cross references, aide memoirs and comments. The performance of these students in exams was recorded. Table 2 shows the average scores of the four groups on two exams.

There is an alarming connection between recording pattern and exam outcome. They may not be related directly through cause and effect, but through some common skill that we did not isolate.

A more realistic way to think of the lecture load is not in words, but in "units of sense"; for example, a formula, equation, structure, graph, or definition. On average, 130 such units were delivered per lecture with a range from 117 to 160. At the lower end of this range students recorded on average 75% of the units; this fell to 52% for the upper end of the range. In other words, the more information there was to be processed, the less efficient the recording (commandment 4) (7). There surely is a lesson here for lecturers: giving more may mean learning less.

The Model Applied to Laboratories

The laboratory is the place for information overload (8, 9). Much has been published about the wonders of laboratories, but not enough about the nonlearning. Think about the situation in terms of the model, and the causes of nonlearning become obvious. A few lines from a laboratory instruction book will serve to make the point. The students have just synthesized a copper(I) complex and are about to analyze it for copper.

"Weigh out 1 g of your white complex and add x mL of 50% nitric acid. When the reaction dies down, evaporate the solution to dryness, cool, and add y mL of water. Now add ammonia solution drop by drop until the solution just becomes cloudy. Add acetic acid dropwise till the solution becomes clear. Add 1 g of potassium iodide and titrate the iodine released with standard thiosulfate".

List for yourself the number of things the student has

to do, the number of important observations that have to be made (color changes, gases evolved, etc.), and the number of theoretical ideas that have to be recalled to make sense of these observations and instructions. The total is staggering! This part was less than one-tenth of what the students had to process in three hours. Is it any wonder that students blindly processed only the instructions and seldom recorded or interpreted the observations (commandment 4)?

First-time, unprepared learners are not in a position to process laboratory experiences with understanding. It does not matter if we use bucket scale or micro scale, the same fundamental problem of overload remains. But notice what the model says (commandment 1). "What we already know and understand controls what we learn." This points to the sheer necessity of some kind of *prelab* to prepare the mind to recognize the expected changes, to be surprised when something different occurs, to have the requisite theory "at the top of the head" to guide what is going to be experienced. This kind of prelab is not "Read your manual before you come" nor is it "Do a few calculations in advance". It must be a more fundamental preparation involving revision of theory, reacquaintance with skills, planning the experiment to some extent, discussion with members of a team about partition of labor, and so on. The student has to be convinced that the experiment is worth doing and that the results will be important and informative. There has to be some feeling of ownership to justify the time spent. The prelab may be a computer simulation to give the student a feel for the procedure and to explore the important variables before going into the lab and doing the experiment.

One of our researchers conducted an experiment involving prelabs and also postlabs. The latter were designed to get students to use what had been learned in the lab to conduct another small experiment with no further instructions. Each group consisted of 100 students. The control group used only the normal laboratory manual. In addition to using the normal lab manual, one group did a prelab, one did a postlab, and one did both prelab and postlab. Demonstrators (mainly graduate students) were asked to keep a diary of the frequency and nature of "thoughtless" questions they were asked by the students—for example "Where can I find 50% nitric acid?" when concentrated acid and water were available. This was only one measurement among others, but the results were all the same. The results for the four groups are shown in the histograms in Figure 4.

A comparison between the first and second clusters of histograms based on four experiments shows that, in every case, the number of "thoughtless" questions dropped for students doing prelabs when compared with those without prelab. The third cluster shows the effect of no prelab, but with postlabs. There is an increase in uncertainty, as might

Will they remember the bangs and pops of a demonstration and totally fail to grasp what you were trying to teach?

Table 2. Mean Exam Score for Each Note-Taking Group

Note-Taking Type	Exam Number	
	1	2
Inaccurate + incomplete	29.3	32.0
Accurate + complete	43.0	49.7
Accurate + complete + verbal communication	56.8	65.5
Accurate + complete + elaboration	75.0	79.0

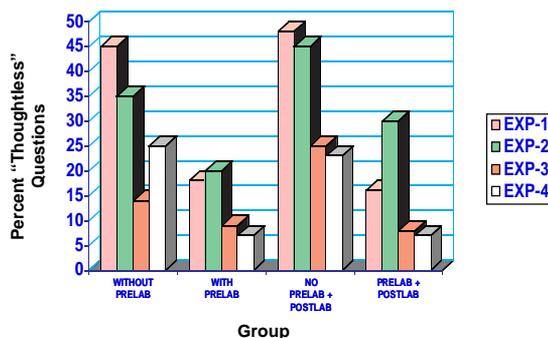


Figure 4. Frequency of "thoughtless" questions asked by students in the laboratory as registered in the demonstrator's checklist.

be expected when the postlabs were applied with no instructions. However, comparison between the third and fourth histogram clusters shows a fall in uncertainty when prelabs are applied before postlabs. The statistical measurements overall showed that the main factor in the students' favorable response to the lab was the prelab.

An experiment recently done in our physics labs took this a step further. Two groups of 85 students conducted four postlab experiments. One group was given a prelab and the other was not. The postlabs served two functions: to anchor the learning in the lab to previous knowledge and to allow the students to use the lab learning to do something original. The postlabs were graded and the results are shown in Table 3. In every case, the students who began with a prelab significantly outperformed those without prelab. This is entirely in line with commandments 1, 2, 3, 7, 8, and 9.

The Model Applied to Curriculum Design

In a longitudinal experiment in curriculum design we began by accepting the commandments and planning a course structure round them before deciding on the chemical content. If previous learning was such an important factor, it was clear that we should consider *prelects* as well as *prelabs*. If *postlabs* were important for consolidation we also needed *postlects*. How were opportunities to be given to students to learn by teaching?

The structure that evolved had this shape. In the conventional course, teaching took place in blocks ten hours long with additional associated lab work and tutorials. It was decided to devote the first hour of each block to a prelect and the last hour to a postlect. This reduced the teaching time from ten to eight hours, but if it produced eight hours of better learning, there might be no real loss. The prelect took the form of a brief quiz on the material

One of the main ways of coping was for students to work on the assumption that if the lecturer went to the trouble of writing something on the blackboard, it must be important.

Table 3. Effect of Prelab on Postlab Performance of Physics Students (1995–1996)

Experiment	Mean Score	
	No prelab	Prelab
Resonance	35.51	47.66
Michaelson Interferometer	48.15	61.60
X-rays	50.59	62.50
Laser	55.88	75.64

that would be essential preknowledge for the block. Answers were given and the students were asked to join one of two camps: those who needed help and those who could give help. The helpers were paired with the "needy" and the prelect continued with tasks in which students could teach each other under supervision. The postlects were designed to link the content of the block with previous blocks and to consolidate. Prelabs and postlabs were treated similarly.

The classes to which this course structure was applied contained a very mixed group of students in terms of their

The postlabs served two functions: to anchor the learning in the lab to previous knowledge and to allow the students to use the lab learning to do something original.

entrance knowledge from high school. Some had done five years of chemistry, some had done none. One would expect that in any assessment the more experienced students would be more successful than the less and least experienced. This turned out *not* to be the case. The mean scores and distributions on all tests for

all groups were almost perfectly superimposable! In fact the top student in the year as a whole came from the less experienced group. A search was made through factors that might explain this (age, personality, gender, math performance, learning style) but none yielded a clue. Our supposition, yet to be proven, is that the *structure* of the learning experience, based upon the model, had enabled all groups to learn well. It would be folly to make unequivocal claims for the success of the model, but we can say that, where it has been applied, our students have had more success with their learning than before.

Some Parting Thoughts

If chemical education is to be a discipline, it has to have a shape and structure and clear, shared theories on which testable hypotheses can be raised. At present we are still in some respects dabbling in chem-ed alchemy, trying to turn lead into gold with no clear idea about how this is to be achieved. Some factions proclaim a touchstone in some pet method such as Problem-Based Learning or Computer-Assisted Learning or Multimedia Learning or Demonstration, while others are dabbling in Conceptual Assessment, Microscale Labs, and fancy textbooks accompanied by teachers' guides. None of these things is bad, but what theory is driving them? Is there any evidence that they are

achieving what is claimed for them? Are we any nearer to making gold?

The fact that students are still, despite our best efforts, voting with their feet and getting out of chemistry, should be telling us something. This is a worldwide phenomenon with just a few areas bucking the trend.

There is surely a message here for chemical educators. Our alchemy is not working. We need to move on in the way that chemistry did in the 18th century. The bits of information gleaned from alchemy had to be fitted together to form patterns and give direction to an otherwise haphazard pursuit of the unattainable.

I have tried to set out in this paper a simple theoretical model that has given direction and stimulus to my own research and that, I hope, has commended itself to the reader. Like any theory, it is incomplete and will be in need of modification and development, but it does deal with pat-

terns of human thinking that are universal and so will give chem-ed research the possibility of findings that will be transferable and international.

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