The Development of Chemistry Teaching

A Changing Response to Changing Demand

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This paper is not intended to be a history of chemistry teaching, but rather a personal view of how chemistry has grown and the forces that have affected its growth. A broader perspective of a philosophy of chemistry teaching also is included.

Until the middle of the 18th century, chemistry existed mainly as an adjunct to medicine, but in the early 1750's a lectureship in chemistry was established in the University of Glasgow and occupied by William Cullen, concurrently with a post in medicine. His successor to the lectureship in chemistry was Joseph Black (1728–1799), who set about systematically teaching chemistry to undergraduates. Pressures from outside the academic world were such as to encourage systematic teaching. The Industrial Revolution was underway, and new interests in "scientific agriculture" were making chemistry important in its own right. Large areas of land were being cleared of peat and marsh, but they were too acid for good agriculture. Black's research on carbonates provided a scientific basis for liming to "sweaten the land". Black also was interested in the phenomenon of latent heat and taught his undergraduates about it. Among those who sat at Black's feet were Benjamin Rush (1745–1813) who became the first professor of chemistry in the USA (Philadelphia); John Maclean, first professor of chemistry at Princeton, and James Watt of steam engine fame.

Black's teaching method was the lecture well illustrated by demonstrations. His exposition was so clear that excellent and complete notes were able to be taken by his students. These remained in circulation among his students for many years and a copy of them turned up for sale in a second-hand bookshop as late as 1936!

Another aspect of Black's work was his set of public lectures designed to satisfy (and stimulate) the demand of a public interested in new philosophy. He clearly was a communicator of the highest caliber and, when he moved to Edinburgh to the "Chair in Chemistry and Physic", he gave up his research and devoted the remainder of his career to teaching (*1*). Chemistry teaching, by the end of the 18th century, was responding both to industrial need and popular interest.

Practical Work

Another man who came under Black's influence was Thomas Thomson (1773–1852), the first occupant of the Regius Chair of Chemistry in Glasgow (1818) at a salary of \$100 per annum! Industrial Pressure for trained chemists had now grown substantially, particularly for analysts to maintain quality control in chemical industry as well as for research chemists. Practical training before this had been on an ad hoc "apprenticeship" basis, but Thomson initiated systematic laboratory training for his students, first in Edinburgh in 1807 and then in Glasgow in 1819. His university colleagues in other disciplines were not too happy about the presence of a laboratory in the old college (the old campus of the University of Glasgow), and he was forced to rent premises nearby in Shuttle Street in 1831 (Fig. 1). When the university moved to its new campus on Gilmorehill in 1870, the chemistry laboratories were "tacked on" as an octagonal outhouse, downwind of the new university buildings (Fig. 2). However, practical, laboratory instruction was here to stay, and undergraduate laboratories sprang up all over Europe and North America. These were devoted to the teaching of skills directly usable in industry and research. It was much later that other rationales for teaching practical work appeared.

Figure 1. Shuttle street labs.

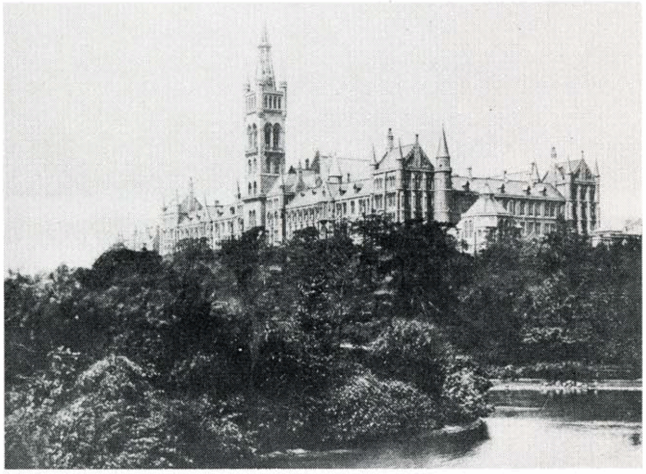

Figure 2. Octagonal Chem Buiilding (now demolished) "downwind" of the main building. R. Kelvin (from which the temp unit is derived) is bottom right.

Chemistry in High Schools

In the 19th century, efforts were made to introduce chemistry into high schools and, at first, it was allowed grudgingly for the "lower classes" who would earn their living with their hands. Eventually, by the end of the century, many schools had admitted "stinks" into the curriculum, but for what purpose? Some students were learning chemistry to enter industry at various artisan levels as laboratory assistants while others were preparing to enter universities and colleges to further their study to graduate level. However, many others were studying chemistry along with other subjects as part of a general education. At this point the teaching of chemistry at high school seemed to lose its way. The classics had always had a place in the curriculum because of their alleged ability "to train the mind", but by the early 20th century the sciences were gradually beginning to move from their utilitarian function (for the few) to compete with the classics as "mind training" for the many. Unfortunately, what was on offer in the chemistry curriculum was largely a catalog of preparations and properties of gases, a list of laws and definitions to be memorized, a few industrial processes with details of temperatures and pressures for regurgitation, and stoichiometric (pseudo analytical) brain-teasing calculations. The practical work consisted of observations of preparations and properties and analytical exercises of varying complexity.

My own teaching career began in a high school in the late 1950's. I was given a "model" student notebook and a textbook and told to teach accordingly. After three years of teaching, I was deemed responsible enough to be allowed to have the key of the stock room. One day, while looking for a piece of rubber tubing, I uncovered a set of model notes dated 1900 that were *identical* to those I was working from in 1960! It was as if chemical time had stood still for over half a century. There was no cognizance of the revolution in chemical theory or of the massive growth of organic chemistry and its associated industry. The Le Blanc Process was still being taught despite the fact that it had long since ceased to operate, and other equally bizarre artifacts were frozen in this chemical time capsule.

However, this situation had not gone unchallenged. Armstrong (*2*) had been trying to persuade educators to take a new look at the science being taught, not just to update its content, but also to look at *why* it was being taught. If it had "mind training" potential, the existing curriculum, with its rote learning, did not provide an appropriate vehicle. He preached the doctrine of Heurism, of free exploration, of capitalizing on the curiosity of the student. This was followed by van Praagh's work (*2*) in which he tried to apply these ideas specifically to Nuffield chemistry. Their work was largely ignored, partly through the inertia of the profession and partly due to the impracticalities that such a free ranging learning mode would impose on an otherwise "tidy" curriculum.

Contemporaneously, a number of people–Piaget, Gagné, Skinner, Bruner, and Ausubel–were grappling with the processes of human learning and asking questions about the nature of what was being learned. Their influence on chemistry teaching was not to appear until some time later, but attention was at last being paid to the learner and not just to content.

The Revolution of the 1960's

Whether there is any truth in the legendary Sputnik story or not, there was a sudden outburst of activity in chemical education in the 1960's (and also in physics and biology). The main features were a massive updating of the subject matter, a movement toward the emphasis of general principles with less stress on individual reactions, and a tendency toward individual "discovery" practical work and away from demonstration, although the latter still existed. This movement was exemplified by *Chem Study* and *Chem Bond* in the U. S. A. and by *Scottish Alternative* and *Nuffield Chemistry* in the U. K. At a meeting in Greystones in Ireland in 1960, an exchange of ideas took place between North America and Europe and was published as "New Thinking in School Chemistry" (*3*).

The chemical content of these new programs was excellent, attractive, and intellectually stimulating, but for whom? Teachers who had themselves been brought up on the plain fare of the 1900–1960 diet found the "principles approach" unifying and emancipating to their own thinking. However, they mistook their own enthusiasm for the enthusiasm of their students. If you never have been in bondage, how can you feel emancipated? If your knowledge never has been fragmented, how can you appreciate unifying principles?

Most of us who were in the business of curriculum development at the time fell into the pit of assuming that what excited us would inevitably excite our students. Have we not seen our own children yawn with boredom when we tell them of how hard life was when we were young and how fortunate they are today by comparison?

Although some of the most able chemists were involved in the 1960's movement, few knew enough about how young people learn to avoid the pitfalls of being carried away by mature enthusiasms.

The sad outcome was that we did not produce a generation of people thirsting for chemical knowledge. In fact, the reverse occurred with enrollments in university and college chemistry falling. As Ogden Nash observed, "It is possible to make progress in the wrong direction".

Could it have been that we had taken much care over the chemical part and had not thought about the education part? In making sure that we had done no violence to the corpus of chemistry had we forgotten (or not known) that human learning patterns may be incompatible with our adult conception of chemistry? The new chemistry has three basic components (Fig. 3); the *macrochemistry* of the tangible, edible, visible; the *submicrochemistry* of the molecular, atomic and kinetic and the *representational chemistry* of symbols, equations, stoichiometry, and mathematics (*4*) .

Those of us who are professional chemists work well inside the triangle with a blend of macro, submicro, and rep-

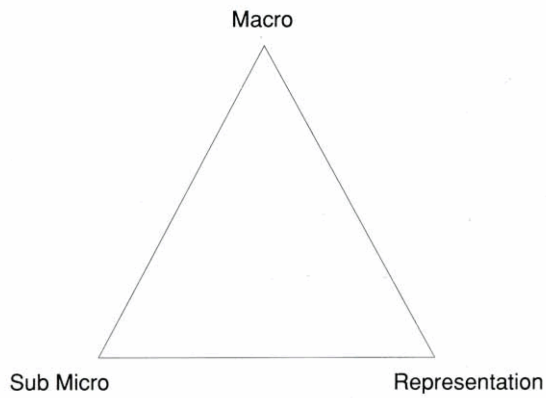

Figure 3. The new chemistry has three basic components: macrochemistry, submicrochemistry, and representational chemistry.

resentational modes. We easily slide from one corner to the other as our thinking requires. As I write, it is snowing and I can slip easily from the beauty of the snow clad roofs and trees, to the hexagonal shape of snowflakes to hydrogen bonding and to the open ice lattice. The children passing my window see it as material for snowballs. The car drivers see it as a hazard. The city sees it as a physical disposal problem. All of these see it as a macrophenomenon at one corner of the triangle. Those who may be thinking of skiing or climbing may see it as a microcrystalline problem, but few, if any, can see the point (or the value) of knowing that it is H_2O with an H–O–H bond angle of 105°. The lattice energy of the hydrogen bonded ice structure does not concern them one bit. They may be interested in seeing a snowflake under a microscope, but this is still near the macro end of the macro-submicro edge. The interior of the triangle is about as real to most people as a "'black hole".

Much of the old chemistry was concerned only with the macro and representational corners and shared edge. The submicro, structural part was often missing and so the middle of the triangle never was explored. It is arrogant on our part to assume, or to insist, that every student studying chemistry for whatever purpose *needs* to operate *within* the triangle. Much useful, helpful chemistry can be taught and learned at or very near the macro corner. I should like to return to this theme shortly.

Chemists Discover Psychology

When the curriculum efforts of the 60's were seen to be less than effective in enthusing or enlightening our students, a group of chemists began to ask questions about learning (as opposed to teaching). These chemists often were misunderstood as dropouts or research failures looking for a new place in the sun. I am not sure that these attitudes have changed much even today! However, we cannot ignore their efforts if we are to address the problems still besetting the chemical education scheme. The "straight" chemists have not solved them despite all their statements about "back to basics" and "dumb students".

A great deal of attention has been given by Herron and his colleagues (*5*) to the work of Piaget, pointing out that there may be a connection between age (maturity) and the complexity of thinking of which a learner is capable. Shayer and Adey (*6*) have gone so far as to analyze the complexity of the thought necessary for understanding each section of the Nuffield chemistry and have shown these often to be incompatible with the age of the students. Mihkelson (*7*) claims to have shown that only about 10% of students entering university in Australia are capable of thinking at the level necessary for the chemistry to be learned. Their "remedy" would seem to be to leave out the complex parts until the students are ready. However, this argument breaks down when it is shown that a given group of students in one discipline may be thinking at a higher level than the same students in another discipline. They are *capable* of the high level thought but *do not use* this capability in chemistry.

Workers in this area recently have tended to change their approach from one of omitting complex chemistry to training students how to use their undoubted abilities to cope with chemistry. Other workers have followed Gagne's ideas (*8*) in which a network can be drawn up to determine the optimum *order* for teaching sub concepts on the way to developing a higher concept. A lot of computer teaching programs owe their shape to this kind of thinking. Experimental evidence for the effectiveness of this has not always been convincing. The individual differences between students cause a breakdown in this hierarchical way of learning. Individuals can make leaps in the network and circumvent what were thought to be essential sub concepts. The networks set out a *teaching* order, but this does not necessarily fit a *learning* order. The work of Keller came close to this pattern of tightly prescribed teaching but not enough attention was given to learning.

A third field of interest has been based upon the psychology of Ausubel (*9*) that lays great stress upon the *internal* mental networks that a student develops for himself or herself rather than upon external teaching networks (Gagné). In this is the implicit idea that every student *constructs his own knowledge in his own way*. Knowledge cannot be passed intact from the head of the teacher to the head of the student. To learn, the student has to "unpack" what she is taught and then "repack" it in a way that suits her previous knowledge and her own learning style.

What is missing in all of this is a mechanism of learning which enables us to understand the learning limitations and, more important, to help the students to circumvent the problems. Such a mechanism is to be found in information processing theory that has grown up alongside the development of the computer. Figure 4 shows one version of this model.

This focusses on learning and the learner and suggests mechanisms in the learning process.

External phenomena represent the things that are clamoring for our attention; things which we might decide to think about with a view to learning them or taking some action on them. For example, when we are driving, we are bombarded with information: colors of houses, different trees, people on the sidewalk, other vehicles, road direction signs, traffic signals, pedestrian crossings, speedometer

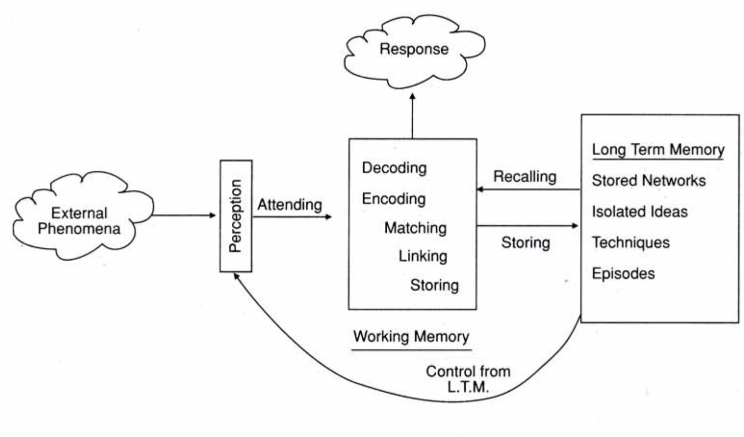

Figure 4. One version of the information processing theory.

reading, and so on. However, we cannot give our attention to all of them or even to many of them at any one time. What we already have in our long-term memory (LTM) helps us to select the important from the unimportant.

What we attend to has to be perceived and decoded. The image on our retina is enhanced (from previous experience), to make a complete image, which is further interpreted. If we decide to act on this information it is encoded for storage or translated into a response. The storage process is most efficient if we can link the new information to something already in LTM. The more similarities and anchorages we can find for attaching the new information, the more easily it will be retrieved.

The LTM seems to have almost infinite capacity for holding information, but the retrieval system is not always efficient (we forget or we cannot find things in the filing system). The model suggests that nothing is really lost but is mislaid.

A second feature that helps our idea of a mechanism is that the space where we hold information while we decode it, allow it to interact with information from LTM and then encode it for storage, is of a very limited capacity. This area is called the Working Memory (WM). To get some idea of its limit, try to hold a *new* telephone number in WM while you multiply the first and last digits together and divide the product by the middle digit. This active, conscious part of the mind is easily overloaded. If we always allowed it to reach this overload stage, we would go insane and so we tend to operate well below overload level and think about only a few ideas at a time, allowing them to interact and become encoded (i.e., they make relational sense with what we already know, or think we know).

Now let us look at the learning of chemistry in the light of this theory. It might help us to understand why chemistry is perceived by our students as hard to learn and why much of our efforts at teaching may be unsuccessful.

Let us begin at the perception end of the model. Our perception of what is important, interesting and understandable depends to a large extent upon what we already have in LTM. Our normal modes of thought about the physical world are macro in nature: mountains, rivers, trees, people, colors, sounds, hardness, temperature, and so on. Our concepts are related to tangible objects. How does a child form the concept of CAT? To begin with everything on four legs may be called a "dog" but gradually, with parental help, the child meets instances of animals with common factors–medium size, furry, pointed ears, whiskers, and so on and these are given the label CAT. Soon the child will admit to this concept (or category) cats of a color he has not met before, and he may even admit a tiger although its size is very different. This has all got to do with an elaborating network in LTM.

But what about the concept of element? We can lay before our students some piles of powder, some black (C), brown (Si) and yellow (S) and say, these are all elements each one consisting of atoms of the same kind. There is *nothing* that appeals to the senses that helps to set out the concept element.

The statement about atoms is not available to the senses either and is drawing upon an idea that the students do not naturally have as an anchoring device in LTM. The problem is exacerbated when we now show some examples of compounds: a black powder (CuO), a brown powder (PbO_2), and a yellow powder (PbO or K_2CrO_4). What is there (which is accessible to the student) to mark out elements from compounds? Any statement about atoms joined in fixed ratios by bonds can only be taken on trust. The experiment which shows that one can get copper from copper oxide really does not help the beginner. Does this *prove* the Cu is a simpler substance than CuO? One can also show that copper oxide is obtainable from copper! This is the kind of dilemma that made chemical theory so late in surfacing in the story of human intellectual development. This is why phlogiston survived so long. Its proponents were not fools. The nature of the concepts was so totally different from most other concepts in the physical world. (This was pointed out as long ago as 1977 by Herron *et al.*, but there is little evidence that any heed has been taken in our curricular design (*10*)).

In trying to "sell" the concepts of element and compound, we are simultaneously having to "sell" the sub micro concepts of atom and molecule and representing all of this by symbols, formulas, and equations. We are in the middle of the triangle I mentioned earlier, before we know it, and few of our students follow us there with any great ease. This new kind of concept takes a long time to grow, but once we have it embedded in LTM we can use it as a powerful way of looking at the world. Our perception of things change: our pictures of snow differ from those who are not initiated into our way of thinking. This is not just a matter of knowledge but of interlinking of a large network of knowledge which conditions our perceptual processes. This may be a slow process that is not helped by cramming chemistry into a two- (or one-) semester course. Ideas and networks need to be revisited often to become well established.

To expect learners to come readily into our chemical triangle and to be able to switch rapidly around it to link macrophenomena with submicro and with symbolism is to ask for overload of working memory.

Our students are like drivers in a strange town who don't know what to attend to and, in trying to process too much, they overload. Their LTM network is not yet well enough developed to enable them to be discriminating. Under these conditions, frustration and bewilderment grow, while enjoyment wanes. Students vote with their feet!

I am not suggesting that chemistry is "at fault", but that it is an intellectual endeavor of a kind that does not come naturally to most learners. Physics can be taught and learned at least at a beginner level, with nothing smaller than a house building brick. Its objects and ideas are tangible, visible, and macro. Where physics begins to meet snags is at the representational level when ideas are expressed in terms of mathematics.

With this insight into learning mechanisms, we are in a better position to think about how chemistry might be learned more effectively by our students.

In chemical research our endeavors are directed and informed by some theory. We design experiments and interpret results against a theoretical background. This enables us to raise and test hypotheses experimentally.

Ought we not to approach our teaching/learning in a similar way? So much of teaching innovation comes into the category of the "good idea" and "taste it and see". Some of the ideas turn out to be splendid while others will not stand the test of time. It could be that some of the successful ones have occurred "more by luck than by good guidance". How much effort could be saved if our teaching/learning innovations were theory driven? The theory need not be "correct" (no theory is), but if it gives direction to our efforts which turn out to be more often successful than not, then that theory is useful. It can be refined so that our success rate increases to the point where it far outpaces our failure rate.

Conclusion

In this paper we traced the beginnings of chemistry teaching as a response to a perceived need, partly industrial and partly social. The methods devised for teaching the small corpus of chemistry at that time are essentially the same as those we are using today to try to teach a much larger and more conceptual body of knowledge for the purposes that are much less clearly defined. Chemistry now finds itself as an integral part of the general education of many young people, but we may not have thought through clearly the implications for teaching it. The subject itself has many problems arising out of its conceptual structure that may be at variance with what we now know about how people learn.

It would seem a reasonable way to make progress if we were to re-examine (1) the nature and structure of our subject, (2) the presentation and methodology of its teaching, and (3) the learning processes themselves.

In my own laboratory we have set out to apply this approach across several areas of chemistry. The work is reported elsewhere (*11–15*) and its outcomes have been encouraging in terms of increased student numbers and enhanced learning.

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