research' approach. In this approach, a small-scale curriculum development is linked to in-depth research on social, content and context specific teaching and learning processes. The structure of the research activities involves repeated cycles (a spiral) of activities, in which each cycle includes the following stages

- an evaluation of a current educational situations;
- formulation of research questions in conjunction with reflection on chemistry and chemistry education;
- development and implementation of new teaching strategies and materials;
- investigation of teaching and learning processes during classroom and laboratory sessions (important research instruments are audio/video-tapes for producing records of laboratory /classroom discussions);
- repetition of the cycle.

The cyclical approach is crucial to the individual teacher and can be used by professional research teams. It allows practitioners to link small-scale curriculum development to more in-depth research. Furthermore, if developmental research is carried out and published by practitioners at secondary level as well as at university level, the results can also help to bridge the gap between chemical education at this interface.

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Chemical Education Research: Where from Here?

PROCEEDINGS

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Introduction

I should like to begin by recording a number of depressing facts about Chemical Education over the past forty years. When we have cleared that ground the remainder of the paper will be a positive attempt to address some of the unpleasant observations.

- Students are not flocking into chemistry thirsting for knowledge. Almost everywhere students are opting out of chemistry.
- Since the early 1960's we have been inundated with chemistry schemes and courses full of promise, most of which have come and gone, leaving the promise unfulfilled. Examples are: Chem. Study and ChemBond from U.S.A., Nuffield and Salters from England, Science for the 70's and Alternative Chemistry from Scotland, ReCoDiC from France and many others.
- As researchers we have solved almost none of the reported problems in chemistry teaching: the mole, bonding misconceptions, misunderstandings about the nature of matter, equilibrium, free energy and many more.
- Research literature has been dominated by work on misconceptions, but little has as yet appeared about how to reverse these or to avoid them altogether.
- Most countries are struggling to find well qualified and competent teachers.
- We are deluding ourselves if we imagine that the general public are taking an increasing interest in chemistry. For normal daily living most people believe that they need no knowledge of chemistry, and maybe they are right.
- A sure way to kill conversation at a party is to confess that you are a chemist. You might as well be a tax-collector or a priest! Your fellow guests say things like:

"I was never any good at chemistry"
"I never understood atoms and molecules"
"I enjoyed splashing about in the laboratory, but I did not understand what I was doing".

All of this is a very pessimistic, but realistic view of the current situation in Chemical Education. Things have gone badly wrong over the past 40 years at some fundamental level.

This period has been characterised by much development activity in the field of Chemical Education. Much has been done to design demonstrations, microchemistry, computer assisted learning, CD ROMs, units on societal issues and a plethora of textbooks. However, most of these laudable activities have been devoted to the transmission of chemical knowledge rather than to any consideration of the nature and desirability of the content or to the nature of the learning process. In other words, we have been emphasising the '*how*' rather than the '*what*'.

The Chemical Education research which has been done has tended to be distorted by the few journals which would accept such material. The Journal of Chemical Education has largely ignored research with less than 2.5% of its articles devoted to it in the issues of 1996-97. The International Journal of Science Education has devoted over a third of its space to work on 'Alternative Frameworks' and this has tended to encourage an approach to research which was negative and offered few solutions to the problems exposed.

The more I have studied chemistry, chemical education and the psychology of learning, the more I have become aware that we are trying to share our beautiful subject with young people in an apparently 'logical' way and, at the same time, conflicting with what we know about the way people learn ('psychological').

I want to spend the rest of this paper attempting to harmonise a *logical* approach to our subject with a *psychological* approach to the teaching of our subject so that young people will catch our enthusiasm and enjoy the intellectual stimulus which our subject can, and should, offer.

Models to help our thinking

Most of my research has been based around two models. The first, *information processing*[1] is an attempt to suggest mechanisms for learning arising from a number of psychological schools. It reminds us that *perception* (how we take a first view of something) is controlled by what we already know and believe. Perception is what we use to select some stimuli for special attention and to filter out others. We look for things which are familiar or which 'make sense' and, if a stimulus does not accord with this, we see it as a surprise or even as something to be avoided or feared. What we already know, enjoy and recognise controls, to a large extent, what we admit through this filter.

The filtered material is admitted into the conscious part of our mind (Working Space) for further processing. Here it is matched with things we know, or modified into a form with which we are happy and then we decide, consciously or otherwise, to store or reject the information.

If we decide to store it, we look for clear attachments in our Long Term Memory[2] on which to fix our new knowledge or experience. In so doing we enrich our large interconnected network of knowledge, experience, belief, preference and prejudice. This new corpus becomes the controller of our next perceptual experience and so the cycle repeats itself. This model exposes some problems which students have with effective learning.

The first of these is that Working Space[3,4] is limited and we can consciously handle only a limited amount of information in a given time. If we try to manipulate too much at once, learning can become faulty or not take place at all, because we just overload and shut down.

A second problem is that if we try to store material in Long Term Memory and cannot find existing knowledge with which to link it, we either 'bend' the knowledge to fit somewhere (maybe completely wrongly) or we try to store it unattached[5]. The 'bending' process leads to Alternative Frameworks[6] or to what is euphemistically called Children's Science. The unattached (or rote) learning is easily lost because it has not been inserted into our mental filing system.

This model can be useful in helping us to think of ways to overcome some of the difficulties we mentioned at the beginning.

My second model has to do with the nature of chemistry. I believe that it exists in three forms which can be thought of as corners of a triangle[7]. No one form is superior to another, but each one complements the other. These forms of the subject are

- the *macro* and tangible: what can be seen, touched and smelt;
- the *submacro*: atoms, molecules, ions and structures; and
- the *representational*: symbols, formulae, equations, molarity, mathematical manipulation and graphs.

Most things which we encounter in the world, and on which we form many of our concepts, are *macro* in nature. We look for regularities and patterns by which to form concepts, but few such tangible observations and patterns exist in chemistry. Even the more abstract ideas such as 'love' or 'justice' are made more tangible by reference to actual examples. On the *macro* level, chemistry is what you do in the laboratory or in the kitchen or the hobby club. This is the experiential situation to which we are accustomed in most aspects of life.

But chemistry, to be more fully understood, has to move to the *submicro* situation where the behaviour of substances is interpreted in terms of the unseen and molecular and recorded in some *representational* language and notation. This is at once the strength of our subject as an intellectual pursuit, and the weakness of our subject when we try to teach it, or more importantly, when beginners (students) try to learn it.

First of all, the simultaneous introduction of all three aspects is a sure recipe for overloading Working Space. Experienced chemists can manipulate all three, but this is not so for the learner. Secondly, when the learner tries to store this triple layer sandwich of information, it is unlikely that he is going to find useful or usable points of attachment in Long Term Memory and so there is an attempt to 'bend' or 'manipulate' the information into a more tangible form and yet another Alternative Framework is born!

Example:

A teacher is trying to show that gases expand on heating and tries to introduce a kinetic picture and even some simple maths. The student remembers that things in general expand on heating, ignores the kinetics and rationalises the experiment by assuming that the atoms have expanded!!

The remainder of this Paper will attempt to show how these two models – *Information Processing* and the *Chemistry Triangle*, can be used to help our teaching by making the logical and psychological coincide. On the way along, we will have to think about the content. What may be logical to us in retrospect, may not be so for the learner. I would like the emphasis to be on *learning* and for teaching to be seen as the means of facilitating the learning process. I suspect that too often 'clever teaching methods' have given more pleasure and insight to the developer than to the learner. In this respect, I must plead guilty, having spent a great deal of time in methodology pursuits without fully understanding the learning process. It is so easy for teachers to confuse their own enthusiasms with that which will enthuse their students.

It is possible, even likely, that as we are devising new methodologies, we are learning something about chemistry for the first time ourselves. But this is learning by someone who is already an expert, not a novice. The insight which has broken through to us may be too 'rich' for a novice to digest.

The use of new technologies in teaching and learning may not be capable of being directly grafted on to our normal education provision without the exploration of the new psychological skills which we and the students have to develop. The television screen is associated, in the mind of students, with the rapid provision of informational 'soundbites' which do not demand deep thought or study. But we are trying to use it to generate what we hope is deep and lasting learning. It is no wonder that so many Computer Assisted Learning packages have proved to be ineffective and unpopular. One time enthusiasts like Norman[8] are now having second thoughts. CAL exponents would do well to read his book before going further. The development of our understanding of these processes (rather than the development of more programs) may be a fertile field for research for some time to come.

I should now like to turn to some actual examples of how we might use the models I mentioned above to help us to take a new view of our research and where it might lead in the future.

Using research to shape the curriculum

Syllabus Order

"Begin where the students are" is an idea as old as time. From an Information Processing point of view, begin with things that they will perceive as interesting and familiar so that there are already concepts in mind to activate the perceptive filter and provide anchorages in their Long Term Memory on which to attach the new knowledge.

Should we begin in the traditional way with salt, sodium carbonate, silver nitrate and barium chloride? Most of these substances are about as real as 'moon dust' to our students and do not provide the psychological framework they need to make sense of what we are trying to teach. This inevitably results in rote learning of undigested material and provides the raw material for the growth of alternative frameworks. They have traditionally been taught first because they are 'simple substances', but are they so simple? Their bonding is not simple either between ions or within ions. Their structures are not simple and they form molecules only in the gas phase or as figments of imagination! The binary compounds also perpetuate, in traditional teaching, the crazy ideas that metals are 'anxious' to lose electrons and non-metals are 'bursting' to accept them. A cursory glance at a table of Ionisation Energies or Electron Affinities shows how crazy this is. These false ideas, which may be alternative frameworks for teachers as well as students, are almost impossible to eradicate later!!

Should we begin with petrol, camping gas, plastics and foods? Organic chemistry has traditionally been thought of as too difficult for beginners, but a moment's thought will show that it is not necessarily so. We are beginning with the *macro* and can afford to take in some *submacro*. Students will accept that hydrogen forms one bond, oxygen two, nitrogen three and carbon four and this is not likely to become an alternative framework which has to be untaught. With this simple idea, you can go a long way in deriving molecular structures. Both corners of the triangle are 'visualisable' and can be made concrete with models. From this, simple formulae arise because the students can count the 'atoms'. There is no need for multipliers and awkward brackets (as in a compound like $Pb(NO_3)_2$). With only these simple submicro and representational ideas you can go a long way through hydrocarbons, alcohols, aldehydes, ketones, esters, carbohydrates, fats, proteins and plastics. Only when we meet carboxylic acids do we have to think about any change in bonding type.

Structures

Intelligent use of models as outlined above leads us into shapes. Some primary school children in Scotland do this as a fun part of their science lessons! (The submicro has become tangible to them, but I have yet to see evidence of the accompanying understanding which the enthusiasts claim).

To help students to rationalise these shapes, we need a new idea, which is easy to make visual, that bonds take up the orientation of minimum repulsion (VSEPR). One bond can point in any direction; two are directly opposite, three form a triangle and four a tetrahedron. This is easily shown by using long balloons to represent the bonds and seeing how they repel each other to form linear, trigonal, tetrahedral or octahedral arrangements. This is more intellectually rigorous than talking about tetrahedra arising from sp3 hybrids. To use the 'unreality' of atomic electronic configurations (isolated atoms in the gas phase) and try to create the reality of molecular structure from them, is intellectually suspect. Without an understanding of the mathematics (which I suspect few chemists have), sp3 or any other hybridisation label, is just mumbo jumbo. It is simply saying that, if you combine one s orbital with three p orbitals, you get a tetrahedral arrangement of orbitals, leading to bonds which point to the corners of a tetrahedron. Pasteur knew this long before orbitals were thought of!!

The Dreaded Mole

The mole concept is perfectly capable of being made tangible provided we do not dissolve it in water and talk about molarity. Kept as an extensive property of matter rather than an intensive property of solution, the mole is not a formidable idea. Students can see that 100 large balls will take up more space that 100 small balls. The idea of comparing like with like is well within their grasp. When this is applied to molecules, the relative volumes of moles of different substances allow us to 'see' the relative volumes of molecules. This holds well as a first approximation, since packing plays a relatively minor role. Measure out moles of an homologous series of alcohols (or other compounds) and set them side by side. The increase in volume between adjacent members in a series is a constant (19 cm^3). Students soon 'see' that the increase must be the addition of one mole of $-CH_2$. There are many more examples of where the mole allows like to be compared with like. Try weighing out equimolar masses of NaCl, NaBr and NaI and pack them into tubes of the same internal bore. It soon becomes evident that the size of Cl^- is less than Br^- and much less than I^-.

Physicists compare things by the kilogram or by unit volume to look for differences such as Specific Heat Capacity and Density. Chemists compare things by the Mole to look for patterns, often constants. Molar Heat Capacities for solid metals are almost constant (the Law of Dulong and Petit) because the same amount of heat energy is supplied to the same number of atoms to change their vibrational energy. If one converts gas densities from g dm^{-3} into the equivalent volume per gram mole we get a constant again. It is instructive to compare the volume of a mole of liquid water (18cm^3) with the volume of a mole of water vapour (22.4 dm^3) to get some idea of empty space in a gas. A test-tube with 18 cm^3 of water alongside a 20 dm^3 drum makes a visual impact! All of this keeps the mole tangible and visualisable.

As you can see, we have tended to remain with only two corners of our chemical triangle at a time, trying to keep new concepts as concrete and visualisable as possible.

We have gone a long way with simple formulae related to reactivity and structure. Nowhere have we balanced an equation or done a volumetric calculation. They have just not been necessary to do good chemistry and good science. The concepts have been kept in a form which tends to avoid Alternative Frameworks.

Moving Towards Inorganic

The *macro* place to start is with metals and their uses. Salts are mostly not within the experience of students and so they have no obvious anchor points within Long Term Memory. Salts arise out of acids and bases and now we have to admit the idea of ions. Many of the wrong ideas that students have, start with ions and salts. Most of the literature on Alternative Frameworks[6] in chemistry is concentrated here and this is not really surprising.

Neutralisation introduced as the formation of water, a familiar substance, might be the place to start before trying to sort out salts. Some very elegant two layer experiments for neutralisation show this well. If a volume of a base weighted with sugar is placed in a beaker, and the same volume of an acid of the same basicity and molarity is floated on top of it, interesting observations can be made. If two long electrodes attached to a battery and meter (or lamp) are lowered just to the interface, a reading is obtained. If the electrodes are pushed to the bottom through the two layers, the reading doubles. If the layers are now mixed completely, the reading drops by a half, indicating that two species of ions are no longer available for conducting current. Where have they gone and what is left still to conduct? Once again we are trying to make visual something which is usually treated abstractly or 'shown' by equations.

It may be that inorganic chemistry and the emphasis on acid/base titrations are historical artifacts of the time when chemistry was almost all analytical. One could be cynical and say that we keep stoichiometry in a prominent position because it is easy to set exam questions on it and easy for students to fail! A large number (maybe the majority) of practicing chemists never balance an equation or do a titration. We know that these operations cause all kinds of trouble for students. Why do we persist with them and cause students such anguish?

However, if we must deal with the mole in solution, our models should be able to help us to arrive at a method less likely to cause trouble.

The traditional way to do an acid/base mole calculation involves a number of steps which are likely to overwhelm Working Memory Space.

- Write formulae for the acid, the base and the products.
- Insert these into an equation and balance it.
- Establish the stoichiometric relationship between the acid and the base.
- Calculate the number of moles of the acid in the given solution and hence the number of moles of base needed for neutralisation.
- Convert the number of moles of base into a volume (if molarity is given) or into a molarity (if volume is given).

Another approach

Now let us apply our models to try to make the process tangible (*macro*) and to reduce the load on Working Space by splitting the problem into three simple steps.

The problem is:

What is the molarity of a solution of sodium hydroxide when 80 ml of it can exactly neutralise 50 ml of 0.1 molar sulphuric acid?

The more tangible steps towards solving it are

- Visualise the beaker containing the acid.
  How many moles of H^+ are in it?
  Molarity $\times$ volume in litres $\times$ no. of H^+ per formula of H_2SO_4
  $= 0.1 \times 50/1000 \times 2 = 0.01$ moles H^+
- Now visualise the beaker containing the base.
  How many moles OH- are in it?
  Molarity $\times$ volume in litres $\times$ no. of OH- per formula of NaOH
  $= z \times 80/1000 \times 1 = 0.08$ z moles OH-
- At neutralisation number of H^+ = the number of OH-
  $0.01 = 0.08$ z
  z = 0.01/0.08 molar
  = 0.125 molar

The reader will notice that no chemical equation and no balancing was necessary.

It is really the old *normality* disguised, but is not the blind $V_1N_1 = V_2N_2$ which was criticised in the past.

A supposed justification for the balanced equation and calculations is that we can calculate yields, but this is only useful if the reaction goes to completion. Industrially, few reactions go, or are allowed to go, to completion and so this argument is doubtful. To use it to calculate percentage yields is another academic exercise. This now leads us to the idea of equilibrium.

Equilibrium

This is another area for Alternative Frameworks and the reasons are obvious from our models. In Long Term Memory there already exists a wealth of knowledge and experience of equilibrium, but not in the chemical sense. However, the language used for both static and dynamic equilibrium is very similar. When the chemist presents equilibrium ideas they easily find points of attachment in Long Term Memory, but almost all are wrong, giving rise to Alternative Frameworks.

Everyday equilibrium ideas have the following features:

- Equal masses (or equal moments) on each side
- Addition to the left makes the system tilt to the left.

Students know this from shopping, riding bicycles, carrying suitcases or walking along a mountain ridge.

Chemical equilibrium does not conform to these ideas, but chemistry students write in exam papers things such as:

"Equilibrium is achieved when the concentration of the products is equal to the concentration of the reactants".

"Apply pressure to the reactants", as if there were a reactants side and a products side.

"Addition of extra reactants changes the equilibrium". What does this mean?

There are quite good analogues available to make this visualisable, but most of them suffer from being 'two-sided' and so can perpetuate a wrong idea in which students forget that reactants and products exist in the same vessel at equilibrium.

Conclusion

In the short compass of a paper it is impossible to set out a whole curriculum for chemistry based on research, but I hope that I have indicated how research can influence our thinking and lead to better teaching and learning. The author is not a reactionary looking backward, but a researcher looking forward by applying research findings to real teaching situations. There is little justification for research for its own sake, but if it can affect practice and bring about benefit, it has a valuable role. I believe that our research has gone far enough already to be able to revolutionise the teaching of our science and other sciences, by bringing the logical and psychological together and so admit many more young people into an appreciation and enjoyment of chemistry.

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