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THE PRACTICE OF CHEMISTRY EDUCATION
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Chemical education in Europe: Curricula and policies

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TEACHING OF CHEMISTRY - LOGICAL OR PSYCHOLOGICAL?

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ABSTRACT: Chemistry is regarded as a difficult subject for students. The difficulties may lie in human learning as well as in the intrinsic nature of the subject. Concepts form from our senses by noticing common factors and regularities and by establishing examples and non-examples. This direct concept formation is possible in recognising, for instance, metals or flammable substances, but quite impossible for concepts like 'element' or 'compound', bonding types, internal crystal structures and family groupings such as alcohols, ketones or carbohydrates. The psychology for the formation of most of chemical concepts is quite different from that of the 'normal' world. We have the added complication of operating on and interrelating three levels of thought: the macro and tangible, the sub micro atomic and molecular, and the representational use of symbols and mathematics. It is psychological folly to introduce learners to ideas at all three levels simultaneously. Herein lies the origins of many misconceptions. The trained chemist can keep these three in balance, but not the learner. This paper explores the possibilities, for the curriculum, of a psychological approach in terms of curricular order, the gradual development of concepts, the function of laboratory work and the place of quantitative ideas. Chemical education research has advanced enough to offer pointers to the teacher, the administrator and the publisher of how our subject may be more effectively shared with our students. [*Chem. Educ. Res. Pract. Eur.*: 2000, *1*, 9-15]

KEY WORDS: *chemical concept formation; macro level; sub micro level; representational level; misconceptions; curriculum; psychological approach to curriculum; curricular order; concepts; laboratory work; quantitative ideas*

* *Editor's note:* This is the text of Prof. Johnstone's plenary lecture for the 5th ECRICE, that he was unable to deliver at the Conference.

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.

1. Students are not flocking into chemistry thirsting for knowledge. Almost everywhere students are opting out of chemistry.

2. 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.
3. 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.
4. 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.
5. Most countries are struggling to find well qualified and competent teachers.
6. 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.
7. 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. 5th ECRICE is a conference for researchers and practitioners and we have to ask ourselves, '*What have we been doing to rectify this situation?*' Things have gone badly wrong over the past 40 years at some fundamental level.

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 lecture attempting to harmonise a logical approach with a psychological approach to the teaching of our subject so that young people, in the next century, 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*, 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 filter out some stimuli for special attention and to ignore 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. 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* on which to fix our new knowledge or experience. In so doing we enrich our knowledge into a large interconnected network of knowledge, experience, belief, preference and so on. This new corpus becomes the controller of our next perceptual experience and so the cycle repeats itself. There are some problems with this idealised picture.

The first of these is that *working space* is limited and we can 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. The 'bending' process leads to *alternative frameworks* 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. No one form is superior to another, but each one complements the other. These forms of the subject are (a) the *macro* and tangible: what can be seen, touched and smelt; (b) the *submicro*: atoms, molecules, ions and structures; and (c) 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. 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!

> *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 '*logical*' and '*psychological*' coincide.

USING RESEARCH TO SHAPE THE CURRICULUM

Syllabus order

Begin where the students are. From an information processing point of view, begin with things that they will perceive as interesting and familiar so that there are already anchorages in their long term memory on which to attach the new knowledge. Do we begin in the traditional way with salt, sodium carbonate, silver nitrate and barium chloride OR do 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 submicro. Students will accept that hydrogen forms one bond, oxygen two, nitrogen three and carbon four. With this simple idea, you can go a long way. 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 above leads us into shapes. Some primary school children in Scotland do this as a fun part of their science lessons!

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. 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 or tetrahedral arrangements. This is more intellectually rigorous than talking about tetrahedra arising from sp^3 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.

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 than 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 and set them side by side. The increase in volume between adjacent members in a series is a constant. 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.

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.

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. They 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 in chemistry are concentrated here. This is not really surprising.

Neutralisation 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 of practicing chemists never balance an equation or do a titration. We know this causes all kinds of trouble for students. *Why do we persist with it 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.

(a) Write formulae for the acid, the base and the products.
(b) Insert these into an equation and balance it.
(c) Establish the stoichiometric relationship between the acid and the base.
(d) Calculate the number of moles of the acid in the given solution and hence the number of moles of base needed for neutralisation.
(e) 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 40 mL of 0.1 Molar sulphuric acid.*

Making it concrete and dividing the problem:

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
$= z \times 80/1000 \times 1 = 0.08$ *moles* OH^-

At neutralisation no. H^+ = *no.* OH^-
$0.01 = 0.08\,z$
$z = 0.01/0.08$ *molar*
$= 0.125$ *molar*

Note that no 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 in several European languages. 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:

(a) Equal masses (or equal moments) on each side
(b) 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 the wrong idea.

CONCLUDING COMMENT

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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