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TEACHERS' CONTINUING LEARNING OF CHEMISTRY: SOME IMPLICATIONS FOR SCIENCE TEACHING

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ABSTRACT: For the past twenty years there has been much research and writing about the 'alternative conceptions' of students in their understandings and learning of science. However, rarely is it suggested that a large range of conceptions is held by their teachers and also by qualified chemists. Substantial data on the alternative conceptions of graduate scientists have been gathered both from personal reflection and experience as well as from more formal educational research. This paper argues that, while such 'errors' should be minimized, they are inevitable, widespread and of considerable significance for the teaching and learning of chemistry. Moreover, it is suggested that there is much to be gained by teachers sharing the insights they have whilst teaching, with their peers and with their students. Accepting the fallibility of authority demands a much more active role for the student and a necessity for a more critical view of the understandings of the teacher. The paper explores the implications for teaching and learning and the relationship between the teacher and student. It highlights the valuation of 'learning' over that of 'knowing' and connects this with epistemological realities of being and becoming a scientist (or an educated citizen). Inevitably, the role of language in science and in the learning of science is a significant issue. [*Chem. Educ. Res. Pract. Eur.*: 2002, 3, 345-359]

KEYWORDS: *alternative conceptions; chemistry learning; reflective teaching; teacher training*

INTRODUCTION

In the context of science (chemistry) education much has been written about constructivism and the ways in which learners make sense of their world by 'constructing' meanings and explanations for themselves (Driver & Easley, 1978; Bodner, 1986; Nakhleh, 1992; Driver et al., 1994; Garnett, Garnett, & Hackling, 1995.) The antecedents of this influential approach to learning science include Piaget, Kelly and Ausubel. The latter of these in his oft-quoted summary of his own work (Ausubel, Novak, & Hanesian, 1968):

"If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly." (p.iv)

provides at least some of the impetus for the volumes of detailed research on *students' alternative conceptions* in science, which has dominated the agenda of science education research for the past twenty years. Johnstone (1999) feels that this agenda has become a

major distraction and deprecates its 'negativity' in focussing on '*misconceptions*'. Moreover, he feels that it diverts research effort away from matters, which would be more productive. These alternatives include:

- (a) The careful interpretation of chemistry curricula to clarify and to relate appropriately the chemistry at the macro-, micro-, and symbolic-levels.
- (b) Exploring and implementing an appropriate information-processing model in teaching, which will attempt to ensure that the short-term memory of the learner is not overloaded.
- (c) Being very sensitive to the importance of language and the whole range of semiotic clues, which together constitute communication in learning and teaching chemistry.

Not everyone, including myself, sees these priorities as being in conflict. Indeed, Taber (2000) has made a significant attempt to produce a synthesis of both perspectives. Doubtless this is a question of balance (Rachelson, 1977; Goodwin, 1994). However, of greater concern is the relative lack of impact that most research into chemistry learning has had on the practice of chemistry education in school and university classrooms and the very small numbers of practicing teachers who have an interest in educational research (de Jong, 1999). This lack of impact to date is recognised in the book published as a tribute to Ros Driver [Miller, Leach, & Osborne, (eds.), 2000] and this also provides visions as to 'how things might become'.

As has been noted elsewhere (Goodwin, 1995; Pardhan, 2001), the educational research focus is very heavily weighted towards conceptions of *students*. Implicitly it seems to be assumed that chemistry teachers (and even more so, 'real' chemists) 'know the right scientific answers'. When such people demonstrate alternative conceptions, for example when teaching lessons or writing books, these 'mistakes' are simply deprecated. Clearly it would be ludicrous to suggest that such professionals *should not know* the facts and understand the theoretical principles of the material they are teaching to others. However, the contention in this paper is that, even though it is clearly better that teachers and chemists should know and understand the fundamentals of chemistry, there is no abrupt, qualitative change in the nature of chemistry knowledge and understanding at the point of graduation or acceptance into the profession. It is argued here that we all carry with us facets of basic chemical knowledge that may not 'pass muster' when subjected to critical examination by others. This is *inevitable* and however much we strive for absolute correctness at whatever level some uncertainty will remain. Even after we have gone through very careful preparation for writing an article or presenting a teaching session there can be no absolute assurance that everything will be correct. Some of the remaining sources of *uncertainty* include:

- The authority from which the material was originally learned or the texts referred to may have become outdated or been in error.
- We may be so sure that we are right that no need is perceived to make any further checks. (Without some confidence in our knowledge it would never be possible to teach, write books or actually do chemistry at all.)
- We may be making the unwarranted assumption that the words we use have the same meanings for everyone else.
- We may not have anticipated questions that arise *as a consequence* of teaching. E.g. new personal insights or questions from even more insightful students may be an outcome of the teaching. In these cases, learning by the teacher *must follow* the teaching.

That this uncertainty can be a good thing is recognised by David Wong (2001) in his editorial to the March edition of *Journal of Research in Science Teaching*:

"It is actually healthier to be slightly unsure about meaning - and thus aware of our uncertainty - than it is to take it for granted."

This paper exemplifies chemistry learning *by the teacher* with examples being taken from four research perspectives:

- (A) Personal reflection.
- (B) Informal, opportunistic-research with science graduate trainee teachers.
- (C) Formal research with science graduate trainee teachers.
- (D) A chemical insight derived from the research and feedback from subsequent debate with colleagues.

These follow approximately the actual sequence in which the learning occurred, although they do overlap and a personal element infuses all of them.

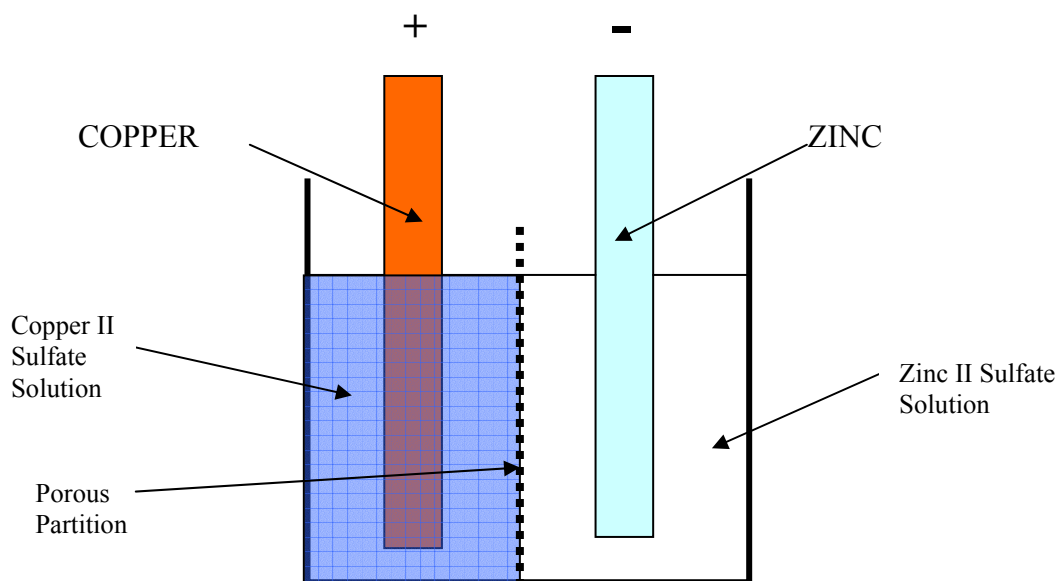
A. Personal reflections on teachers' learning

In this section I provide three examples that enhanced my learning: (i) by asking myself critical questions; (ii) by students asking me critical questions; (iii) by students arguing that I was mistaken

(i) Asking myself critical questions

In 1962, during my first term of teaching, I was dealing with methods of determining molecular weights with an A-level class (students aged 17). For substances that can be readily vapourised one of the methods to be used was that devised by Victor Meyer in 1882 (see for example Findlay (1954)). This has long since been lost from the A-level chemistry syllabus, but my students were expected to be familiar with the procedure and to be able to perform appropriate calculations.

Essentially the method of Victor Meyer consists of maintaining the temperature of a bulb at the lower-end of a long glass tube, about 30°C above the normal boiling point of the substance under study. When the system is at equilibrium at the prevailing atmospheric pressure, air ceases to be expelled into the measuring equipment attached to the top of the tube and a small weighed sample of the substance is dropped into the hot bulb. Here it rapidly vapourises and displaces a volume of air into the measuring apparatus. My teaching notes and my memory of my own A-level studies emphasised the following points. (a) *The volume of air displaced needed to be measured at the prevailing atmospheric temperature and pressure* and that (b) *the actual temperature of the bulb was irrelevant provided only that it was constant and well above the boiling point of the sample under test*. As I was presenting this to the class I asked myself the question 'How can this be?' for the first time. Surely the vapour at the high temperature would occupy a greater volume than the volume of air at room temperature. My students did not ask the question, but subsequently I realised my misconception. Before the introduction of the sample, the air in the apparatus was a fixed volume at a constant, although not uniform, temperature. When equilibrium was restored after the sample fully vapourised, the conditions were identical and therefore the tube contained the same *number of gas molecules* (Avogadro's Hypothesis). The test sample displaced NOT an equal volume of air, but an equal number of air molecules. Avogadro's hypothesis suddenly became more meaningful and significant to me although not, on this occasion, to my students.



Electrode reactions (when the plates are connected)

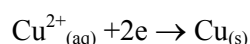
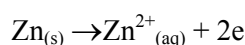


FIGURE 1: *A Daniel cell (simplified).*

(ii) Students asking me critical questions

On another occasion, whilst trying to explain the operation of a Daniel Cell (see Figure 1) a student surprised me by asking the question: “How can it be that copper is deposited on the positive electrode? Surely the positive ions will be repelled?” I had no immediate answer. (NB: It is just as difficult for students to see why positive Zn^{2+} ions should leave the negative electrode.) (This problem was also identified by de Jong, 1999.)

In very brief summary, the explanation I found to be satisfactory is that when circuit is completed electrons flow from Zn to Cu. This disturbs the electrode equilibrium, which has been established at both electrodes. At copper, Cu^{2+} are deposited in order to (attempt to) restore the positive equilibrium electrode potential. At the zinc, Zn^{2+} ions pass into solution in an attempt to restore the negative charge on the zinc to the equilibrium value. It is *not* the charge on the electrode that *causes* the ionic drift and electrode reactions (c.f. electrolysis). (See also Ogude & Bradley, 1996)

(iii) Students arguing that I was mistaken

A third example of a critical incident dates from about five years later whilst teaching A-level in another school. The subject under discussion was ‘oxidation numbers of elements’ and, on this occasion, the students’ thinking appears to be more sophisticated than my own:

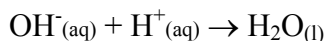
We were reviewing the various definitions of oxidation and reduction that the students had met

earlier in their course with the aim of extending these to include the idea of oxidation number. Having explored many examples, including copper II ions (Cu^{2+}), manganate VII (MnO_4^-), hexacyanoferrate III ($\text{Fe}(\text{CN})_6^{3-}$), chromate VI (CrO_4^{2-}) and dichromate VI ($\text{Cr}_2\text{O}_7^{2-}$), students seemed to be understanding and making connections. Even the example of fluorine oxide (F_2O) in which oxygen has an oxidation state of +2 caused interest rather than stress. Oxidation states of carbon initially caused no problem $\text{C} = 0$; $\text{CO} = +2$; $\text{CO}_2 = +4$. However, the huge range of oxidation states entered by carbon as hydrogen is successively replaced by chlorine, although readily accepted as successive oxidation, was perceived as outrageous for what was seen as 'not a very fundamental change' (see Table).

TABLE: *The wide range of oxidation states of carbon.*

Compound	CH_4	CH_3Cl	CH_2Cl_2	CHCl_3	CCl_4
Oxidation state of C	-4	-2	0	+2	+4

A test was given a few days later in which students were required to identify the oxidising and reducing agents as appropriate in particular reactions. One item happened to be:



Clearly there is no formal change in oxidation number of either hydrogen (+1) or oxygen (-2) during the neutralisation process and I marked wrong the answers from the most able students in the group who suggested that the hydrogen ion *oxidises* the hydroxide ion when they combine. The other students mostly agreed with me that neither oxidation nor reduction had occurred although one argued that the hydroxide ion had had hydrogen added to it and was, therefore, reduced.

In fact the students had spent a long time after the lesson explaining to each other and rationalising the oxidation states of carbon described above. They had convinced themselves that the key was to examine minutely the shift of electrons, which would be expected when changes around a particular atom occurred. A change from CH_2Cl_2 to CHCl_3 caused a jump in the oxidation state of carbon from 0 to +2 and this, they argued, was caused by a relatively small shift of electrons from the carbon atom when hydrogen was replaced by chlorine. *They convinced me* that a significant and probably equally large shift of electrons would take place away from the oxygen atom when a hydroxide ion joins with a hydrogen ion. Agreed, this does not change the oxidation state, but "So what - you told us that removal of electrons is oxidation - surely all chemists agree to that". I gave them the mark, hoped that all chemists did agree *and* that the A-level examiners did not use this example in a question relating to redox. I guess I am still convinced by my students, but have found few others who link redox and neutralisation with the insight of these students.

The above example does not close down discussion on this redox issue and doubtless some readers will find it exasperating (in that it exemplifies a significant deviation from the syllabus, a waste of time and a danger that students will lose marks in the examination). Others will find it frustrating (because students so rarely take such an interest and present such challenges) and yet others will be fascinated (because it extends their own perspectives on redox reactions). My own reaction was a mixture of all of these. I believe with intensity in the reverse order to which they are presented above. This is a real example and its significance was enhanced for me by its rarity. For the class concerned the behaviour was typical. They were determined to make sense of the subject. At the time I felt uncomfortable since I felt I had 'lost control' but at the end of the course:

- The students all passed the A-level examination with the top grade, or up to three grades higher than the one estimated by me. The five most able students had also been entered for the 'special paper' and all gained distinctions.
- All students were confident to ask questions and to insist that things which were taught were consistent and made sense to them. It seems significant that much of the debate took place outside the classroom/laboratory and did not involve me directly.
- As the teacher I probably learned more chemistry from this two-year course than from any other comparable period during my life.

B. Informal research ('Simple' kinetic theory)

The following piece of work is fully described in Goodwin (1995), but was significant at a professional level for me in that it legitimated and reinforced the question 'How do scientists understand basic science?'

By this time (1992) I had been working in teacher education for almost thirty years and had become Head of Department. On this occasion, because of staffing difficulties, I found myself taking a single afternoon session on 'teaching the kinetic theory' to a group of graduate science students who were in the process of becoming secondary school science teachers. As part of the session students, in small groups, were required to use this theory to explain a number of 'simple facts' to students and to produce a single overhead transparency to enable them to share their ideas with the other groups. One of the 'simple facts' was that an exothermic reaction, e.g. that between hydrogen and oxygen, does not occur spontaneously at room temperature. Part of the transparency from this group is reproduced as Figure 2.

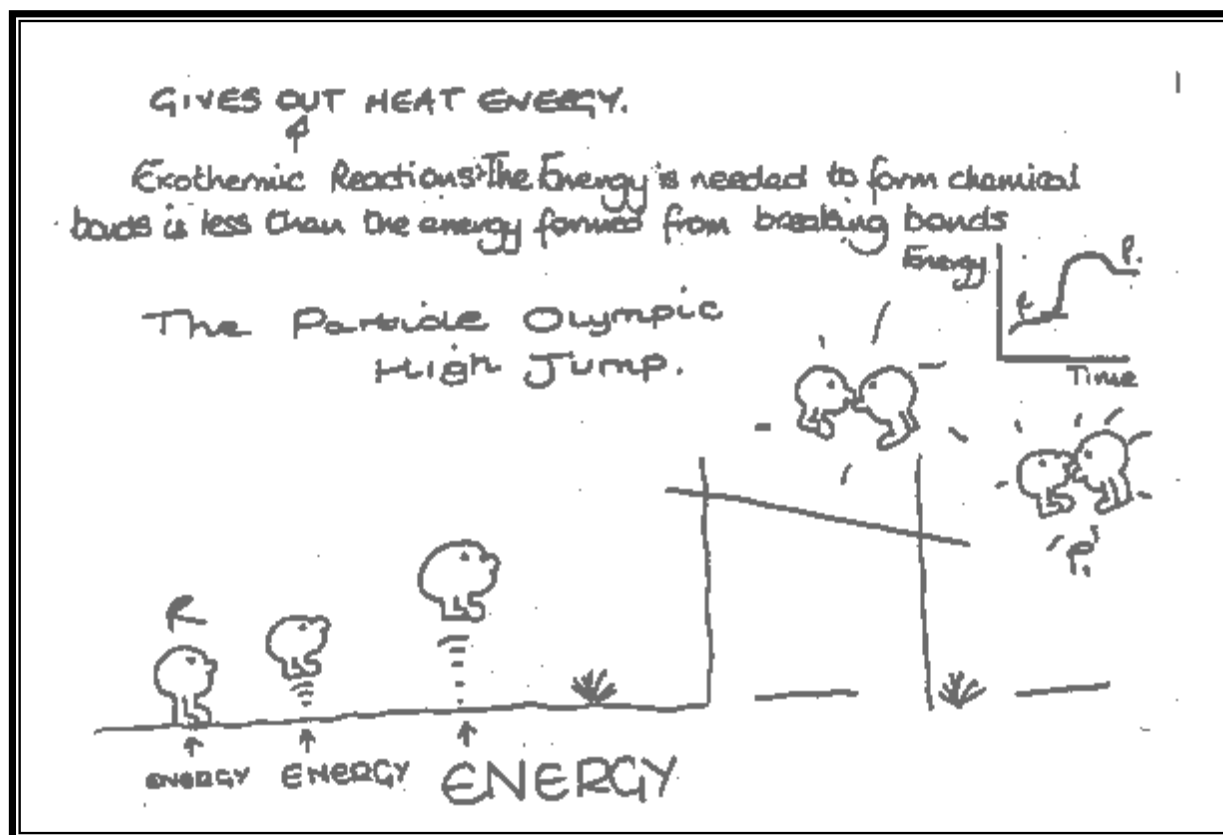


FIGURE 2: 'An exothermic reaction does not occur spontaneously at room temperature.'

It should be stressed that students had only about 30 minutes to complete the task and they had no prior warning. Close inspection of Figure 1 shows a number of alternative conceptions (misconceptions) including:

- Energy is needed to form chemical bonds and is given out when they break.
- The energy diagram seems to represent an *endothermic* reaction.
- The x-axis on this diagram has been labelled 'time'.
- The large diagram seems to indicate an 'activation energy barrier', but the interpretation of a *reaction process* from it is difficult, for me at least.

Subsequently it transpired that the first statement had been taken directly from a school science textbook. Presumably the author could not claim to have been taken unawares. When these results were presented at the 3rd European Conference in Research in Chemical Education (ECRICE) in Pisa, Italy in 1993, I was a little disconcerted to find that my own interpretations raised almost as many comments as did those of my students.

C. Formal research (*Evaporation and boiling*)

During the academic years 1995-97 the opportunity arose to undertake a more formal study exploring the knowledge and understanding of a later cohort ($N = 52$) of graduate scientists who were training to become teachers. Some of these results are described in Goodwin (2000b) and a full description has now been published (Goodwin 2002).

Three of the more surprising findings from this study were:

1. That just less than one third of the students expected that the temperature of water would fall when it was allowed to evaporate freely. A majority expected that the temperature would not change. A common reason given for this (wrong) conclusion was to the effect that "*The temperature and state of a substance cannot change at the same time. The state is changing from a liquid to a gas and thus the temperature must remain constant.*" In the context of pure liquids melting and boiling I can remember teaching that 'rule' but I was surprised to find it being so widely (mis) applied here.
2. Half of the cohort indicated that the content of the large bubbles seen in water that had been boiling for a long time was indeed *only* water vapour (steam, water or even water-gas). This is only slightly 'improved' over results reported from students aged 13-17 by Osborne and Cosgrove (1982) and alternative conceptions covered a similar range (Goodwin, 2000b). However, one of the graduates, a physicist, added to the options available by sharing his belief that the large bubbles contained a *vacuum*. He applied this explanation consistently in a subsequent answer relating to water boiling at room temperature under reduced pressure.
3. One of the scenarios explored in the research was the opening of two cans of 'cola'. Both were allowed to stand undisturbed for a long time and *one* of them shaken vigorously immediately prior to opening. Less than 20% believed that the pressure inside the shaken can remained unchanged. The almost explosive result on opening the shaken can as well as the 'obvious' explanation that energy is transferred to the can by shaking seem to be *very* convincing. 'Unfortunately', from this viewpoint, the amount of energy transferred to the contents of the can is infinitesimal compared to that required to raise the temperature, and hence the pressure, sufficiently to explain the effects observed.

Both cans were at equilibrium at the start and shaking would not affect the equilibrium position unless there was a significant temperature rise. The 'correct' explanation must be based on a kinetic effect (Deamer and Selinger, (1988)). Only one respondent in the research approached an explanation from a kinetic perspective and he predicted that the pressure would rise.

In all of the above examples 50% or less of the respondents, all of whom hold bachelor's degrees or higher qualifications in science, gave a 'wrong answer' to what would appear to be a straightforward (everyday) science question. The third scenario was included mainly because it was a common situation involving bubbles but also because I had just been made aware of, and convinced by, the kinetic explanation. Clearly this turned out to be the most problematic and was probably the one least likely to have been considered within a formal science course. I must stress that there is no suggestion here that the students *should have known* the 'right answers' despite my surprise for the first two that they did not. This is especially so since there was no prior notice of the 'test'. The large majority of the respondents was successful in gaining qualified teacher status and is now in the fourth year of secondary school teaching.

The results of this study matched very closely those of a pilot study carried out in the first year in partnership with a colleague in Bogota (Colombia) (Goodwin and Orlik, (2000)). The only significant change in the questionnaire between the pilot and the larger scale study was the inclusion of the question '*Is the cola boiling when the can is opened?*' in the latter. It is the debate on this question, which proved to be highly controversial that forms the final perspective in this section.

D. Insights derived from the research and subsequent (ongoing) debate with colleagues (*Fizzing drinks are boiling?*)

That fizzing drinks are examples of boiling solutions was an idea that struck me as I was writing up the results of the pilot study described in section C. Initially the idea seemed outrageous, although I doubt that my colleague in Colombia is convinced even now. Thus the question was included in the main study. 96% of the respondents believed that the cola was NOT boiling. (This compares to 73% who agreed that forced evaporation by blowing air bubbles through liquid hexane *is not* an example of boiling and the 73% who agreed that water, bubbling at room temperature, when the air pressure on the surface was reduce *is* an example of boiling. These were the expected 'correct' answers.)

The certainty with which my idea was dismissed was impressive, although probably not surprising since up until a few months earlier I would have believed that fizzing drinks were not boiling. The most common objections to the idea are:

- (a) Fizzing is simply the release of gas (carbon dioxide) and the cola itself is not changing state.
- (b) The liquid has not been heated; there has been no increase in temperature.

The response from one of the physicists is illuminating since clearly he has applied his formal understanding to the context, but does not see the carbon dioxide as a solute, which affects the vapour pressure of the solution. It seems that this contains the core difficulty that we all experience/d?

"I would reserve the word boiling to refer to the evaporation of liquid (solvent) at the point where its saturated vapour pressure has reached external pressure. I don't believe the vapour pressure of water in the cola has reached atmospheric pressure."

My own more detailed rationale for considering that fizzing drinks are examples of boiling liquids is now in print (Goodwin (2001)). It is, however, the debate ensuing from presentations of this idea at a number of conferences as well as the reactions to this paper that will be the focus here. Presentations include the 17th Biennial Conference on Chemical

Education (BCCE) Waterloo, Canada, 1998; 5th ECRICE, Ioannina, Greece, 1999; 18th BCCE, Ann Arbor, USA, 2000; and 18th International Conference on Chemical Education (ICCE), Budapest, Hungary, 2000.

A small majority of the 40 or so written and less formal communications I have received has been accepting of the thesis that fizzing drinks *are* boiling although no-one claims to have seen them that way previously. The thesis has also been seen as sufficiently sensible to be discussed in a number of teacher training sessions around the world. Most interesting for me, however, is the passion aroused in those people who *know that I am wrong* and the reasons that they put forward:

Foremost among these is an anonymous reviewer of the manuscript of the paper referred to here. (Fortunately the Editor and other reviewers felt the idea interesting and worth debating.) This I quote in full since it encapsulates and clearly articulates points also made by others:

- *“General evaluation: F Not suitable for publication (d) Contains errors*
- *The beverage has been carbonated at a pressure of CO₂ higher than the normal atmospheric pressure. This follows Henry’s law: $m_2 = k_2 P_2$, where m_2 = mass of gas dissolved; P_2 = pressure of gas; k_2 = Henry’s law const. The gas under the bottle cap is then CO₂ saturated with H₂O vapor. When the cap is removed the liquid degasses until it is at equilibrium with the CO₂ partial pressure in the air. This is a relatively slow process since CO₂ dehydration kinetics are slow.*
- *This has nothing to do with boiling. The boiling point of a liquid is reached when the vapor pressure of the liquid equals atmospheric pressure. This will be higher than 100°C because of the boiling-point elevation caused by the dissolved substances in the soda pop.*
- *This paper is absolute nonsense and must not be published.*

Notwithstanding the final *coup de grace* the chemical argument is impeccable except that CO₂ is not recognised as one of the solutes in the soda pop solution. Otherwise, s/he surely would not have expected a boiling point elevation since the CO₂ vapour pressure would contribute to the vapour pressure of the liquid i.e. carbon dioxide *solution*. S/he does, however, make explicit in the second paragraph that both CO₂ and H₂O are present in the vapour phase in equilibrium with the liquid soda pop.

The use of the technical term ‘degasses’ in the second paragraph is interesting since a few others also used it. The term is usually applied to the removal of dissolved air or other gases from a solvent (or a surface) prior to its use in a synthesis or a manufacturing process. Degassing is normally achieved by applying a vacuum and sometimes heat as well. Extending my thesis a little further I would suggest that the bubbles of air that ‘degas’ from water when it is heated or subjected to a vacuum is also an example of ‘boiling’ - of an aqueous solution of air.

For most people, especially those outside the scientific community, the idea that fizzing drinks are boiling is a ludicrous one. The need for boiling things to be hot seems central to the meaning of the word in everyday language. Unless one is comfortable with the idea that liquids such as hydrogen, oxygen and ammonia do boil at temperatures well below the freezing point of water, fizzing drinks are not in the frame. It is also necessary to appreciate that *bubbles within* a liquid cannot form unless the saturated vapour pressure of the liquid is at least as high as the pressure on the surface of the liquid. However, in this instance some chemical educators and chemists still find an equation between fizzing and boiling contentious if not ridiculous. Some other comments follow:

- *The saturated vapour pressure of the water is clearly not equal to atmospheric and therefore the drinks cannot be boiling.*

- *The Cola does not turn into a gas and therefore the drinks cannot be boiling.*
- *Only liquids can boil and fizzing drinks are solutions. (This was said with great passion and conviction.)*
- *Carbon dioxide gas is in the solution. It is not a liquid.*
- *Liquid carbon dioxide is in the can and it is this that escapes when the drink fizzes. The drink is not boiling, but the carbon dioxide may be.*

Implicit here seems to be a belief that it is the solvent that boils and solutes either escape (degas) if they are much more volatile or they remain behind as the solvent boils away if they are non-volatile. These beliefs are surely not compatible with conventional chemists' explanations of say, fractional distillation of a hydrocarbon mixture found in crude oil? I have one comment from a chemical engineer who maintained that dissolved methane and ethane 'flash off' from the system. He did not see these as part of the fractional distillation process because they pass straight through the fractionating column. Presumably the escape of these was seen as 'degassing' the crude oil at the start of the fractional distillation process before boiling of the rest of the mixture occurs.

DISCUSSION

It seems that, although all chemists and most science teachers would claim to 'know and understand' about solids, liquids, gases, evaporation, boiling, melting and dissolving, there are some remarkably varied and sometimes apparently arbitrary and inconsistent conceptions around these very basic ideas. It seems that even among chemists, teachers and teacher educators there is no clear 'right' answer to questions such as the following:

- When salt solution is boiled (above 100°C at normal atmospheric pressure) is the solution boiling? (Or, is it only the water that is boiling?)
- Is the salt in the solution in the liquid state?
- Does a gas enter the liquid state of matter when it dissolves in a liquid?
- Is dissolving carbon dioxide in water a physical or chemical change?
- Is the spontaneous escape of (wet) bubbles of carbon dioxide from fizzing drinks properly termed 'boiling'?

Of course, you may already know the answers for certain. I am not sure you would give me full marks if you were marking my test paper!

A very telling statement was made about people's understandings of science (Levy-Leblond, 1992):

"There is no single knowledge gap between scientists and non-scientists, but there is, instead, a multitude of specific gaps between specialists and non-specialists in each field." (p.17)

Specialists within a narrow field may well agree on answers to the simple questions above, but only if a mutual agreement on these terms is necessary for their specialist communication. Otherwise they will have left the questions where they found them in their school science lessons and tests. It may be surprising, but it is doubtful that there will be any overall consensus.

Does this matter? Surely all scientists *should agree* on the meaning of basic words in our vocabulary? Unfortunately it seems that this can never be the case since our words carry with them *our* interpretations, experiences, beliefs and sometimes even our emotions. When others receive the same words it is *their* meanings they hear. Words do not restrict their

meanings to one particular definition even if there is a meaning carrying the IUPAC endorsement. During any communication therefore, it is essential to check, and where necessary negotiate, so that the words have congruent meanings for all parties. It is too much to ask that the words have the *same* meanings, especially when considering exchanges between novice learners (students) and more experienced learners (teachers).

In the wider scheme of things it does not really matter whether neutralisation is a redox reaction or whether carbonated drinks boil when poured into a glass. That is unless the belief of your teacher/examiner differs markedly from your own. This provides pressure for students to learn (and be taught) right answers that do not necessarily make sense. The key concern here is that we learn to tolerate that there can never be a uniform set of meanings for words within the scientific community. We must expect meanings to develop and be prepared to renegotiate meanings as we learn.

I am now moving onto difficult ground since, in a recent draft paper, I clearly upset another reviewer. My suggestion was that "*emphasising too strongly* that salt does not melt when it dissolves in water *might* constitute a barrier to chemistry learning at a later stage." The following is a direct quote from the comment:

"One of the obstacles to science learning at any level is that students arrive saturated with misinformation and sloppy reasoning skills; the challenge of science educators is to develop patterns of careful thinking. Not only do I NOT believe that careful terminology at the elementary school will 'constitute a barrier to subsequent chemistry learning', but I consider it the obligation of teachers to impart to their students valid science unsullied by the 'fuzziness' of everyday speech."

There is, of course no argument for careless reasoning or 'sloppy' vocabulary, but surely it is part of any pattern of careful thinking that meanings and significance of words and ideas are constantly re-evaluated? It is not helpful in the long term to learn meaningless words by rote.

This relates to the wider issue of teacher competence. The 'official view' that teachers must completely know and understand science before they teach has, hopefully, been challenged and somewhat softened, if not undermined. However, if understanding specific and basic scientific facts and theories is not the main prerequisite for teacher competence then what do we put in its place? I would submit, on the basis of discussions with fellow tutors, (Goodwin 2000a) that the competence required is an ability and confidence to, not only present science to their students, but also to *contend* science with their students. This involves not only the content of science but also:

- A rationale for its inclusion in the curriculum, which goes beyond its presence on a syllabus or the possibility of a question on an examination.
- The meanings of the subject in the context of the wider curriculum and implications for society and individual students.
- An appropriate balance between passing examinations and learning science.
- A continuing enthusiasm for *learning* by the teacher.
- Most importantly, the critical engagement of students.

If they are to see themselves as successful in this task the teachers must engage their students in these processes such that the students develop their own autonomy in learning. Clearly, the teachers require a robust and consistent story of science for themselves but it must remain legitimate for them to be continually learning and 'not to have known' before they began teaching. We perhaps need to consider the passionate advice from Richard

Dawkins (2002):

“What matters is not the facts but how you discover and think about them: education in the true sense, very different from today’s assessment-mad exam culture.”

Uncertainty, ambiguity and fuzziness are inevitable and form an integral part of the epistemology of science. There is certainly an important ‘question of balance’ to be settled. (Rachelson, (1977), Goodwin (1994)), but it seems that we need to let more *uncertainty* into science education. Certainly students need to accept that ‘sense making’ is integral to the doing and learning of science. This is why we *try* to use words carefully, define terms, state laws as clearly as possible and continually match and rematch these ideas with experience and the ideas of others. Things are, however, always changing. It is impressive to read, say in the ‘Genome’ (Ridley, (2000)) of the large number of ideas that were not even available to think about, let alone apply in biology, biotechnology and medicine as recently as 1995. In particular such ideas could not be available prior to qualification for any but the most recently qualified science teachers. However the ideas must impact on a science (even chemistry) curriculum, especially since they raise important and controversial issues, which are on the agenda of humanity during the early 21st Century. Uncertainty in science, language and complex situations is the central thesis of “From Certainty to Uncertainty” (Peat, 2002).

Suggesting that science education should be *less certain* seems to be a dangerous conclusion and if overdone, or done carelessly, it could be harmful. However trying to make science education a little more kin to science surely is appropriate? Currently it seems that we have an epistemological dichotomy between science and science education. Science education is being pushed, in the UK at least, towards greater certainty, greater emphasis on test and examination scores, greater bureaucratic accountability and less flexibility, autonomy and professional satisfaction (and fun) for science teachers and their students - all in the name of higher standards. This contrasts with some of the movements and curriculum developments of the 1970s and 80s. Perhaps there was too little certainty and consistency during those times but we now seem to be losing balance in the opposite direction. Some uncertainty legitimates, indeed requires questioning, contribution, debate, invention and ideas from teachers and students. Too much uncertainty makes science too complex, difficult to learn and impossible to teach.

Reference to the value of *an appropriate flavour of uncertainty* was made earlier (Wong, (2001)) and very strong appeals for this have indeed been made by others, as the quotations below demonstrate:

(a) Richard Feynman (1963) - published 1998.

“I feel a responsibility to proclaim the value of this freedom to teach that doubt is not to be feared, but is to be welcomed as the possibility of a new potential for human beings. If you know you are not sure you have a chance to improve the situation. I want to demand this freedom for future generations. (p.28)

(b) Ibid. *“People say to me, ‘Well, how can you teach your children what is right or wrong if you don’t know?’ Because I’m pretty sure of what is right and wrong. I’m not absolutely sure; some experiences may change my mind. But I know what I would expect to teach them. But, of course a child won’t learn what you teach him.” (p.67)*

(c) Robert May (UK Government Chief Scientist) (2000)

"Most peoples' encounter with science in primary school, secondary school and even in universities, is through courses that teach stuff that (scientists) thoroughly know. So most peoples' encounter with science is as a set of things we* really understand, whereas, of course the really interesting problems tend often to arise when we are beyond the frontier and we don't understand. All the areas of dispute and excitement and worry are in the relatively small, but disproportionately important areas where we do not really understand things yet. For that, the intuition shaped by what you do in school is inappropriate."* (pp.28-29)

(*Perhaps it would have been more realistic to say 'think they'?)

However the dangers of 'certainty' from a completely different perspective, that of policemen, are painted in the following quote. It might equally apply to some pedants and some pedagogues?

(d) Arundhati Roy (1998)

"But they understood each-other perfectly. They were both men whom childhood had abandoned without trace. Men without curiosity. Without doubt. Both in their own way terrifyingly adult. They looked out at the world and never wondered how it worked, because they knew. They worked it." p.248.

CONCLUSION

Construction of our meanings and understandings is a necessary feature of all our experiences. A spread of alternative conceptions is an inevitable part of the human condition. The science being learned by any individual is at the boundary of their experience and, if it is to be useful it must be significant and make some kind of sense. Teachers themselves gain insights by learning with their students and this requires mutual respect of ideas as well as continuous critical evaluation in both directions. A requirement here is confidence and trust in and by teachers and students. In particular we need an appropriate humility and willingness to continue to learn from the teachers and scientists who 'think they know'. Questioning and uncertainty must be legitimate within the framework and development of national guidelines, syllabuses, programmes of assessment and patterns of qualification. It is a 'question of balance', but it *seems* that if we are to make progress in becoming scientists or doing science - and perhaps even in remaining human - nothing must ever be *quite* certain.

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REFERENCES

- Ausubel, D.P., Novak, J.D. & Hanesian, H. (1968). *Educational psychology: A cognitive view* (2nd edn.). New York, Holt Rinehart & Winston.
- Bodner, G.M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education*, 63, 873-878.
- Dawkins, R. (2002). The joy of living dangerously. *Guardian Review* 6th July (<http://books.guardian.co.uk/review/story/0,12084,749875,00.html>) accessed Sept 2002.
- Deamer, D.W. & Selinger, B.K. (1988). Will that pop bottle really go pop? An equilibrium question. *Journal of Chemical Education*, 65, 518.
- Driver, R. & Easley, J. (1978) "Pupils and paradigms; A review of the literature related to concept development in adolescent science students." *Studies in Science Education*, 5, 61-84.
- Driver, R., Squires, A., Rushworth, P. & Wood-Robinson, V. (1994) *Making sense of secondary science: Research into children's ideas*. London, Routledge.
- Feynman, R.P. (1963). Published 1998. *The meaning of it all; Thoughts of a citizen-scientist*. Reading, Massachusetts, Addison-Wesley
- Findlay, A. (1954). *Practical physical chemistry* (8th edn.). London, Longmans Green (revised by Kitchener J A).
- Garnett, P.J., Garnett, P.J. & Hackling, M.W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education*, 25, 69-95.
- Goodwin, A. (1994). Wonder and the teaching and learning of Science Education. *Science*, 159, 8-9.
- Goodwin, A. (1995). Understanding secondary school science: a perspective of the graduate scientist beginning teacher. *School Science Review*, 76 (276) 100-109.
- Goodwin, A. (2000a). Subject knowledge testing and initial teacher education. *Science Teacher Education*, 27, 15-16.
- Goodwin, A. (2000b). The teaching of chemistry: Who is the learner?' *Chemistry Education: Research and Practice in Europe*, 1, 51-60. [http://www.uoi.gr/conf_sem/cerapie]
- Goodwin, A. (2001). Fizzing drinks, are they boiling? *Journal of Chemical Education*, 78, 385-387.
- Goodwin, A. (2002). Evaporation and boiling – Trainee science teachers' understandings. To be published in *School Science Review*.
- Goodwin, A.J. & Orlik, Y. (2000). An investigation of graduate scientists' understandings of evaporation and boiling. *Revista de Educación en Ciencias*, 1, 118-123.
- Johnstone, A.H. (1999). "Chemical education research: Where from here?" The Royal Society of Chemistry, Chemical Education Research Group Lecture given at the Variety in Chemistry Meeting at Heriot Watt University. Reprinted in *University Chemistry Education*, 4, 32-36.
- Jong, O.de. (1999). "Crossing the borders; Chemical education research and teaching practice" The Royal society of Chemistry, Chemical Education Research Group Lecture given at the Variety in Chemistry Meeting at Heriot Watt University. Reprinted in *University Chemistry Education*, 4, 29-32.
- Millar, R. Leach, J. & Osborne, J. (Eds.), (2000). *Improving science education: The contribution of research*. Buckingham, The Open University Press.
- Nakhleh, M.B. (1992). Why some students don't learn chemistry. *Journal of Chemical Education*, 69, 191-196.
- Ogude, N.A. & Bradley, J.D. (1996). Electrode processes and aspects relating to cell emf, current and cell components in operating electrochemical cells. *Journal of Chemical Education*, 73, 1145-1149.
- Peat, F.D. (2002). *From certainty to uncertainty: The story of science and ideas in the twentieth century*. Washington DC, Joseph Henry Press, ISBN 0-309-07641-2.
- Pardhan, H. & Bano, Y. (2001). Science teachers' alternate conceptions about direct-currents. *International Journal of Science Education*, 23, 301-318.
- Rachelson, S. (1977). A question of balance: A holistic view of scientific inquiry. *Science Education*, 61, 109-117.
- Ridley, M. (2000) *Genome* New York, Harper Perennial.

- Roy, A. (1998) *The god of small things; a novel*. New York, Harper Perennial.
- Taber, K. (2000). "Molar and molecular conceptions of research into learning chemistry: Towards a synthesis" The Royal Society of Chemistry, Chemical Education Research Group Lecture (CERG Lecture No 3) given at the Variety in Chemistry Meeting at Lancaster University. A synopsis of the lecture is given in the 'Proceedings'. A full version is available at: <http://www.rsc.org/lap/rsccom/dab/educ002.htm> (accessed June 2002).
- Wong, D. (2001). Editorial. *Journal of Research in Science Teaching*, 38, 280.