Developing robust and coherent conceptions of chemistry: An integrated model

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Introduction – Misconceptions and the Conceptual Change Model

The process by which students develop conceptions of science has long been an area of science education research. From a constructivist standpoint (Bodner, 1986) the formation of misconceptions and processes of conceptual change are equally interesting, as learners may place unintended interpretations onto instructional materials. Previous studies have identified a myriad of individual misconceptions across the sciences (Azizoğlu, Alkan, and Geban 2006; Boo 1998; Cakmakci, Leach, and Donnelly 2006; Sneider and Ohadi 1998; Taber 1996) and the efficacies of numerous interventions have been investigated (Cakir, Uzuntiryaki, and Geban 2002; Diakidoy and Kendeou 2001; Kalkanis, Hadzidaki, and Stavrou 2003; Yang, Greenbowe and Andre 2004). General theories of conceptual change have also been proposed, attributing the origins of misconceptions to ontological miscategorisations (Chi, Slotta and de Leeuw 1994), conflicts with epistemological presuppositions (Vosniadou 1994; 2002), and inappropriate selections from multiple representations (Hallidén, Petersson, Scheja, Ehrlén, Haglund, Österlind and Stenlund 2002; Spada 1994).

Despite this extensive body of research, the practical implementation of recommendations from general conceptual change theories remains problematic. Much of the research is necessarily and appropriately learner-centred and thus individually-focused; however, undergraduate teaching is primarily conducted in groups. Conceptual change theories have also offered comparatively little overt advice for general pedagogical practices to minimise misconception formation. This paper is intended to begin to fill this gap, by offering an integrated model for developing robust conceptions which is applicable at the classroom level. The empirical data presented draw on research in chemistry education, but the model presented is expected to be applicable in other science domains.

Before considering existing conceptual change models, it is important to understand the intention of the term ‘misconception’. The use of this term has been criticised for focusing on the ‘wrongness’ of a student’s conception, and terms such as alternative conception and naïve conception have been proposed (Sneider and Ohadi, 1998). Criticisms have also been made by sociocultural theorists, who argue that students may simultaneously hold multiple conceptions for a single phenomenon, and that it is the appropriate selection of a situationally useful ‘tool’ that is important (Hallidén et al., 2002). In chemistry, students are expected to select and appropriately utilise Arrhenius, Brønsted-Lowry, and Lewis theories of acids and bases, for example. Conceptions which are inconsistent with modern scientific perspectives may still retain a high degree of utility in limited circumstances. After all, the Aristotelian notion that ‘motion requires a mover’ is highly useful if you want to move a piano. Nevertheless, it is unarguable that some student conceptions are not only totally inconsistent with modern scientific principles, but also have no utility for any reasonably conceivable situation.

Vosniadou and Brewer (1992) investigated young children’s conceptions of the Earth, finding that a fish bowl model, with humans living on the flat base at the bottom, is common amongst young children (see Figure 1). Such a synthetic model develops as children attempt to reconcile their experience with the teaching they receive. It serves no useful educational purpose, but does allow the children to function in their classroom environment. In this paper, the term ‘misconception’ is intended to refer to conceptions such as this, which would lead a student to scientifically unacceptable inferences and which have no everyday application. The term is not intended to imply that students cannot hold multiple conceptions, nor that scientifically inappropriate conceptions are necessarily bad provided their zone of applicability is recognised. Nevertheless, a term recognising the wrongness of conceptions which impede students in developing robust scientific understandings (conceptions which ideally need to be altered or replaced entirely) has been chosen deliberately.

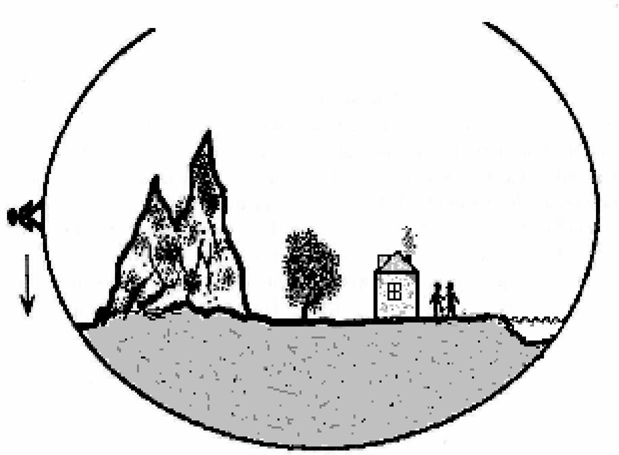

Figure 1. A fish bowl model of the earth, adapted from Schnotz and Preuβ (1999), where people live on a flat surface at the 'bottom', and which does have 'ends', which people are prevented from reaching by mountains and oceans

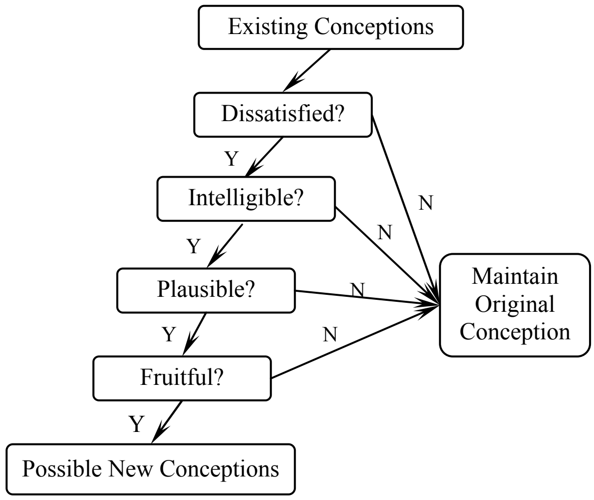

Figure 2. A representation of the Posner et al. (1982) conceptual change model, adapted from Dole and Sinatra (1998)

One of the most influential models of conceptual change was developed by Posner, Strike, Hewson, and Gertzog (1982), and is illustrated in Figure 2. According to this model, changing conceptions requires that a learner recognises the limitations of their existing conception, which is presumed to lead to dissatisfaction. The student must then find the potential new conception to be intelligible (if not understood in all respects), plausible, and fruitful (in that it assists in explaining observations or solving problems – tasks not previously achievable) for conceptual change to be possible. This model has been criticised on several grounds, including that it implies a linear sequencing of events that is not borne out in practice, and that it presumes that recognising the existence of a conflict in conceptions will necessarily result in dissatisfaction. Strike and Posner (1992) have noted that their model was intended more as an aid to research design, and was not meant to be taken as advocating a particular pedagogical approach to conceptual change teaching.

Nevertheless, the Posner et al. (1982) model remains extremely useful in at least two areas. Firstly, it assists in interpreting situations in which conceptual change teaching sequences are ineffective. For example, Müller and Wiesner (2002) found that university students maintained Bohr model conceptions of the atom despite a semester of instruction on quantum mechanical approaches. Given that students generally conceive of electrons as hard spherical particles (Mashhadi and Woolnough 1998), one could predict that quantum mechanical models drawing on concepts of particle-wave duality might lack plausibility for students. Depending on levels of mathematical competence, quantum mechanical reasoning may also not be intelligible. Secondly, the conceptual change model identifies three factors critical to the formation of robust conceptions – intelligibility, plausibility, and fruitfulness. This paper argues that an additional factor is needed – coherence.

Method

Data presented here come primarily from qualitative and quantitative investigations of examination scripts of students enrolled in the Chemistry 1 for Veterinary Science unit at The University of Sydney in 2003 and 2004. Scripts were examined for broad thematic categories as part of a content analysis, following the general approach of Miles and Huberman (1996). Interpretations were checked using semi-structured interviews with 11 volunteers from across the two cohorts (2003 enrolment: 93, 2004 enrolment: 100). Other results from this project have been reported (Read, George, Masters, and King, 2004, 2005), establishing that the participants are representative of the entire cohorts.

Results and discussion

A robust understanding of a topic requires internally coherent connections between its constituent areas, whilst robust appreciations of a domain require in addition coherent inter-topic connections. A multiple choice question common to the end-of-semester examinations for both cohorts asked students to select which of five elements was unlikely to be redox active in a biological system. The response patterns are shown in Figure 3, where it is clear that students chose either tungsten (a distractor) or the correct answer. Interview data suggest that students had difficulty recognising which part of their chemistry knowledge was relevant – likely due to a lack of coherent connections between topics such as redox chemistry, ionisation energies, and the biological periodic table. As a result, they resorted to strategic approaches, selecting tungsten due to its lack of familiarity:

'Like, there were no… tungsten was… not in anything… at all… ever … I think it was because, like, tungsten was unfamiliar. So, I thought: "Oh, that won't be redox. Won't be. We would have done it if it was redox active in a biological system."'

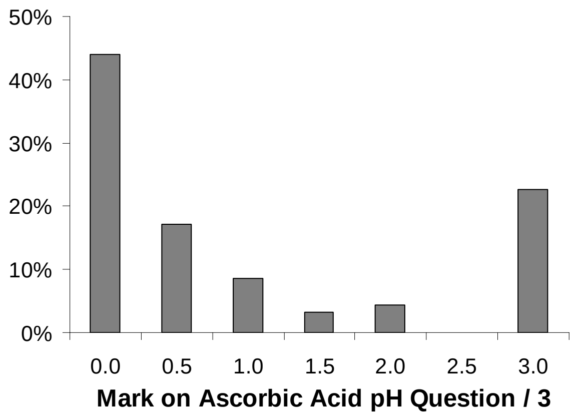

Figure 3. Distribution of responses to a multiple choice question about an element unlikely to be redox active in a biological system

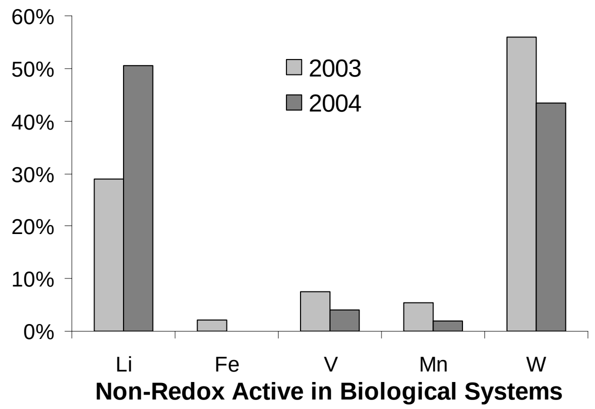

Figure 4. Distribution of marks on acid/base question 1, concerning the pH of a 0.1 M ascorbic acid solution, from the 2003 examination

The importance of intra-topic coherence is illustrated by students' approaches to two acid / base questions which appeared consecutively on the 2003 end-of-semester examination:

1. Ascorbic acid (Vitamin C) is a monoprotic acid of formula $C_6H_8O_6$. Calculate the pH of a 0.10 M solution of ascorbic acid, given the K_a of ascorbic acid is 8.0×10^{-5} M.
2. Write equations to show what happens to a buffer solution containing equimolar amounts of $C_6H_5CH_2COOH$ and $C_6H_5CH_2COOK$ when (a) H_3O^+ is added, and (b) OH^- is added.

Students performed well on Question 2, with 77% able to write correctly both equations. However, as Figure 4 shows, students found question 1 challenging, with nearly half of them scoring zero. Amongst students who use an appropriate approach, nearly all scored full marks. Content analysis of the approaches taken by students who made any incorrect attempt showed that 71% tried to apply the Henderson-Hasselbalch buffer equation to solve the problem. This points to a lack of genuine understanding of buffers, as aqueous ascorbic acid is not a buffer system, and shows the impression of substantial understanding of buffers created by students' performance on question 2 is misleading.

The standard misconceived approach demonstrated metacognitive skills of planning, but not reflection (Ertmer and Newby, 1996; Hartman, 2001; Schraw and Moshman, 1995). Students determined that they needed to find the concentration of the ascorbate ion in order to apply the Henderson-Hasslebalch equation (demonstrating planning) – unfortunately, they generally attempted unjustifiable stoichiometric approaches to try to find this value. Ultimately, these calculations demonstrated that the students also held misconceptions relating to stoichiometry, acid strength, and conservation of mass. Overall, the evidence from this pair of questions supports the conclusion that students had a fragmented view of several topics, with a serious lack of coherent connections between their various conceptions. Findings from the 2004 cohort support this conclusion. In that examination, sequential questions asked about the pH of an acid / conjugate base salt mixture, and about its suitability as a buffer. Most students correctly used the Henderson-Hasselbalch equation to calculated the pH, but many proceeded to declare the system a poor buffer on grounds such as its pH not being 7. Again, fragmented knowledge lacking coherent connections is evident, with algorithmic mathematical ability not reflecting conceptual understanding. However, it is also clear that some of these fragments in isolation are both fruitful and intelligible to the students.

A final example comes from a question dealing with amino acids, in which students needed to provide the structure of cysteine (Cys) having been given its side chain, and were then required to draw its dipeptide, Cys-Cys. Performance on the first part was strong, with 84% of students answering correctly, but 47% of this group were unable to answer the second part of the question. Figure 5 shows a variety of responses from students who were able to provide an acceptable Cys structure, retaining (as far as practicable) the original constitutions and geometries. The errors seen here range from incorrect peptide linkages to scrambled molecular structures to violations of bonding and charge rules. All of these structures point to a lack of coherent connections between organic chemistry and related general chemistry concepts such as bonding and conservation of mass. This incoherence was even more pronounced in the group unable to answer the first part of the question – this group offered numerous answers which might best be described as molecular fragments.

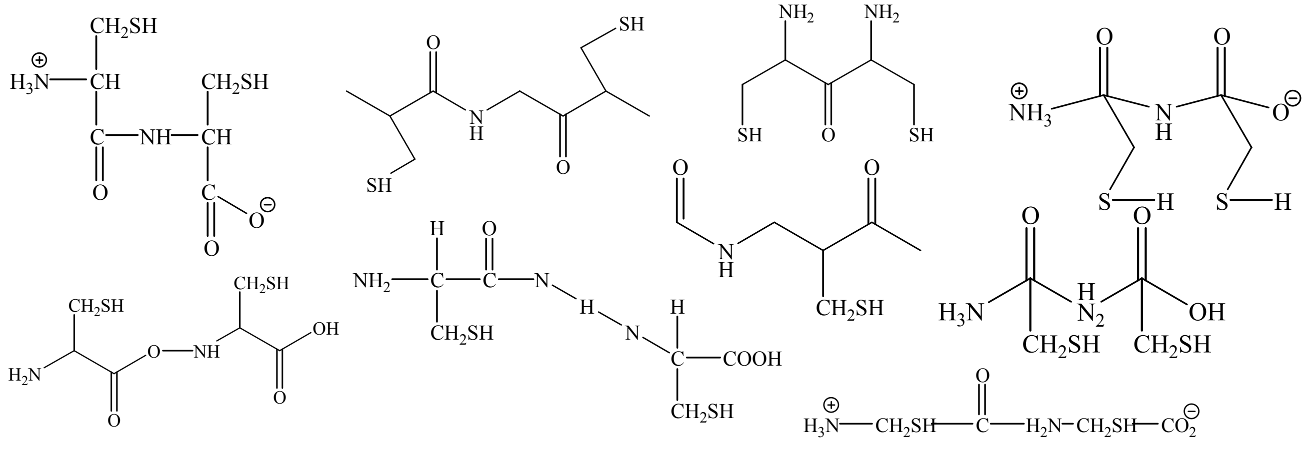

Figure 5. Student structures for the dipeptide Cys-Cys, drawn by students who provided a constitutionally-acceptable Cys structure. The top left Cys-Cys structure above shows the correct constitution for the neutral pH zwitterion (that is, $^{+}H_3NCH(CH_2SH)CONHCH(CH_2SH)CO_2^{-}$).

Collectively, these examples point to the importance of both inter- and intra-topic coherence, and also highlight its associations with making conceptions fruitful from a student perspective.

Understanding such connections would better equip students to recognise the implications of theory which they encounter, thereby influencing intelligibility and likely also plausibility. Whilst the students in this study have exhibited numerous distinct conceptual difficulties with these questions, all would be assisted by instruction focussing on connections both within and between topics. All would also benefit from improved metacognitive skills of reflection and self-evaluation (Masui and De Corte 1999), as a high level of inappropriate satisfaction with answers is also evident here.

An Integrated Model for Robust Conceptions

One of the strongest criticisms of the conceptual change model is its omission of motivational factors (Pintrich, Marx and Boyle 1993), which are an integral and critical aspect of learning (Pintrich 2003) that have been increasingly included in discussions of conceptual change (Sinatra 2005). As a motivational construct, interest can be divided into situational interest, arising from characteristics of the learning activity and its surrounding context, and individual interest, which reflects an enduring personal disposition towards a topic (Hidi, Renninger and Krapp 2004). These categories have been further sub-divided into triggered and maintained situational interest, and emerging and well-developed individual interest, with movement through these levels of interest being associated with improved effort, engagement, and depth of understanding (Hidi and Renninger, 2006). Interest can also be linked to improved self-regulation via the self determination theory of Ryan and Deci (2000).

Figure 6 illustrates an integrated model for developing robust conceptions. Based on empirical findings presented here and related work, coherence has been placed at the centre of a cycle linking Posner et al.'s (1982) intelligible, plausible, and fruitful criteria. Appropriately structured examples (Ward and Sweller, 1990) can use the fruitfulness of working through a solution to improve the intelligibility of the relevant theory for students – this illustrates one reason for using a cycle rather than a linear structure for the criteria. Improved planning, reflection, and self-evaluation from metacognitive control process development (Georghiades 2000) and motivation through fostering interest are included as inputs to the overall teaching approach. This theoretical model begins to address limitations in the classroom-level applicability of previous models, and also incorporates and connects with previous conceptual change theories. Vosniadou's (2002) synthetic models arise when instruction clashes with presuppositions and such presuppositions need to be addressed before moving on to the concept in question; coherent connections between these learning activities will then require construction. Notions of multiple representations (Hallidén et al. 2002) require students to appreciate the boundary conditions which govern the circumstances of their use, necessitating the connections between such circumstances being intelligible and coherent.

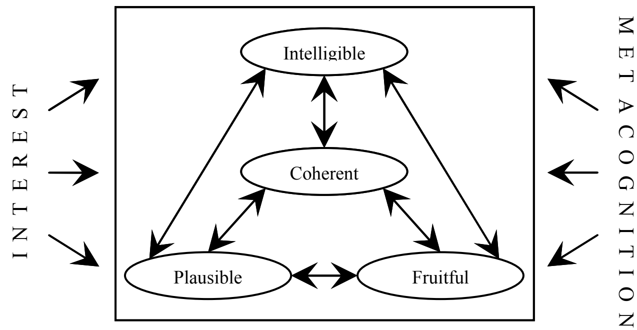

Figure 6. The core of an integrated model for a teaching cycle for the development of robust conceptions

As an example of applying this model, an instructor could provide students with an incorrect approach to the ascorbic acid question, and then use a think-pair-share approach to challenge the students to identify as many errors in the approach as possible. Such an activity is essentially a reflective critique, assisting students in developing metacognitive control processes, whilst fostering interest with a situational interest trigger for performance oriented students. The responses provide the instructor with the opportunity to explore the origins of each error, allowing inter- and intra-topic connections to be highlighted. Indirectly, such a discussion is highlighting the self-evaluation which makes the implausibility of the approach taken evident, refuting potential misconceptions, and improving the intelligibility of whatever theory is under consideration.

The model can also be used to support a teaching approach which begins by highlighting a need for new theory by demonstrating some inadequacy in current approaches – in other words, by showing the potential for a more fruitful new approach. In the case of the ascorbic acid question, this might be achieved by starting by trying to estimate the pH using the approaches available for strong acids. Such an approach could easily demonstrate that the pH must satisfy $1.0 < pH <$ neutral pH, and could lead to a discussion of the size of this range in terms of concentration (reinforcing the implications of the logarithmatic nature of the pH scale). Once the students have learned about calculating the pH of weak acid solutions, the approximation approach could be revisited as facilitating informed reflection on the reasonableness of the final answer – also modelling an important characteristic of the problem solving approach of experts, which are known to be qualitatively different from those of novices (Mayer and Wittrock, 1996; Voss and Post, 1988).

As a final example, instruction which includes explicit modelling of metacognitive activity can also be used to promote coherent connections and facilitate the development of robust schema. Taking the amino acid question above as an example, some students' answers did not conserve the structure of the parts of the reactant molecules which are uninvolved in the reaction. If an instructor were to verbalise conserving molecular structure as they draw in these moieties within the product molecule, students' attention is drawn to the importance of considerations beyond the site of reaction. Explicitly checking that the product obeys bonding and charge rules models for the students the relevance of such considerations; this not only highlights the connections between different areas of theory (bonding rules and organic reactions, in this case), but also provides students with a window into the usually-hidden thought processes of an expert engaged in problem solving. A detailed discussion of approaches to modelling metacognitive processes, along with the potential benefits for student learning in organic chemistry, will appear shortly (Read, George, Masters and King 2007).

Conclusion

The empirical data presented in this paper highlight problems with students' conceptions across several chemistry topics, with all showing incoherent or absent inter- or intra-topic connections. Students' ability to answer correctly isolated questions can create overly positive impressions of conceptual understanding, with consideration of related questions providing evidence of fragmented knowledge. Combining these results with existing conceptual change research, an integrated model for developing robust and coherent conceptions of chemistry, applicable for design of classroom level learning activities, has been proposed and some possible classroom application explored.

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