TEACHING ABOUT THE BOOK OF NATURE: THE CHALLENGE OF DEMYSTIFYING CHEMISTRY AT SCHOOL LEVEL

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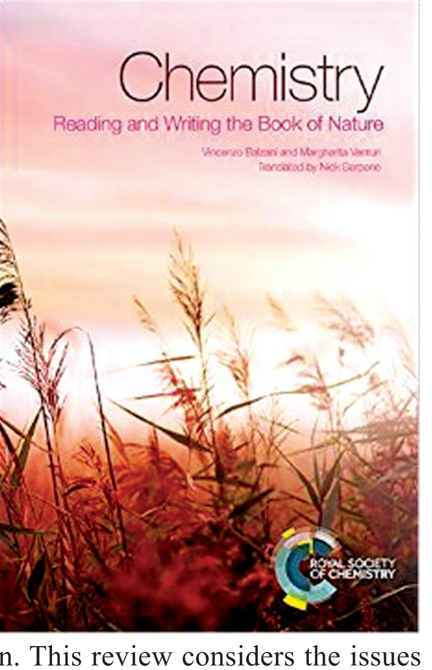

Introduction

This book is a translation of an Italian title (*Chimica! Leggere e scrivere il libro della Natura*) which was shortlisted for an Italian award for popularisation of science, and has been published in translation by the Royal Society of Chemistry. The book "sets out to introduce chemistry concepts and demystify chemistry showing how it is a major part of our everyday lives" and to present "arguments and suggestions to be considered when teaching chemistry in secondary schools, together with a simple teaching approach so that students can understand and come to appreciate the language of chemistry and its experimental practices". The authors are chemistry professors based at the University of Bologna, but it is not clear from the book whether they have experience in teaching chemistry in schools or working in teacher education. This review considers the issues raised by 'Chemistry: Reading and writing the book of nature' from the perspective of scholarship and research in the fields of chemistry education, and more widely science education.

The intention of Professors Balzani and Venturi "to introduce chemistry concepts and demystify chemistry showing how it is a major part of our everyday lives" seems to be strongly motivated. They suggest that the reaction of people to finding out one is a chemistry teacher can be one of shock, as "why would an intelligent, normal person want to teach a subject as incomprehensible and as hazardous as chemistry?" (p.5). Perhaps there are cultural differences in attitudes or simply in norms of politeness, but I did not recognise that as a common reaction in my own (English) national context. However, perhaps this is indeed a reaction that chemistry teachers commonly face in Italy. This aim then seems to suggest the book is largely addressed to the general public - perhaps to offer current school students as well as those who left school unimpressed with chemistry an alternative perspective: that of a subject of great relevance to our everyday lives. Again, there was a lack of resonance here with my impression of the public perception in my own context where the importance and relevance of chemistry, and science more widely, tends to be acknowledged, *even though* most people are happy enough that someone else understands and applies chemistry for them, and so they do not need to directly engage with the subject themselves.

The intention of demystifying chemistry for the masses is accompanied by, or perhaps is meant to be achieved through, advising school teachers on how best to teach the subject. The blurb on the back cover reports that "the book presents arguments and suggestions to be considered when teaching chemistry in secondary schools, together with a simple teaching approach so that students can understand and come to appreciate the language of chemistry and its experimental practices". These multiple purposes certainly raise a question about the intended readership. Readers needing an introduction to, and demystification of, chemistry will (one hopes) not be charged with teaching the subject and so will not need to consider adopting arguments and suggestions relating to teaching chemistry in secondary school. Those who do teach chemistry and so are in a position to consider and possibly act on advice about how to teach the subject should not need the introductory material.

That however ignores the possibility of presenting introductory material within a text in a manner that exemplifies a new pedagogic approach, which the authors could then discuss. This is, to some extent at least, what Balzani and Venturi actually do: they offer an introductory account of chemical concepts and of the importance and relevance of chemistry – and then offer suggestions for a teaching approach that is in keeping with their own presentation. So the book can be considered to be intended as a pedagogic thesis illustrated by an exemplar text.

The authors themselves actually claim that their book is written for "students at the junior and high school levels, as well as the general reader" (p.vii), yet presumably by including material on teaching approaches they are also hoping their book will be read by teachers and others with influence on school chemistry. Whilst there are some points of science that can be quibbled with, it is the authors' claims to be offering and exemplifying new teaching priorities and approaches which invites a detailed consideration.

This book therefore deserves evaluation from a pedagogic perspective, with a focus on how Balzani and Venturi go about introducing and 'selling' chemistry to their potential readers. Now this is a relatively slim volume, whereas chemistry education is an active field populated by a range of theoretical perspectives and an extensive canon of observational and experimental studies exploring the effectiveness of different teaching approaches in various educational contexts (Gilbert et al., 2002; Taber, 2015a). This raises the question of the extent to which the authors' thesis is informed by scholarship in the field that can support and develop their arguments about how chemistry should be taught in schools.

Balzani and Venturido do not *explicitly* engage with such scholarship at all. So there are no citations to educational research to support the authors' approach and arguments, but then such a style of writing would likely be unappealing to most general readers. Yet, if they are also writing for teachers, one might wish them to seek to support their arguments and recommendations. Teaching is intended to be an evidence-based and research-informed profession (Taber, 2013a), and one might wonder why chemistry teachers should change what they teach, and how they teach it, unless there is good research evidence to show this will improve teaching and learning, student engagement, and/or eventual public understanding of the subject.

A somewhat unorthodox approach to explaining chemistry

The opening sections of the book are not explicitly concerned with teaching, but with introducing key chemical ideas and explaining the relevance of the subject. The authors claim that "many believe that chemistry is a sterile and boring science" (p.vii). 'Many' of course is a vague notion, and similar claims could surely be made about any school subject. The authors aim to "set straight…such preconceived views" and to do so by "demystifying chemistry by describing, in an understandable, albeit somewhat unorthodox way, some of the fascinating notions of chemistry…" (p.vii). For the educator, then, Balzani and Venturi claim to offer an account of chemistry through what they present as a "somewhat unorthodox" pedagogic text.

The extent to which Balzani and Venturi's approach is genuinely unorthodox is a moot point. They suggest being selective in what subject matter is taught, arguing against teaching great swathes of material for its own sake. This has already been widely recommended in the literature (Osborne & Collins, 2001), although not always followed through in practice. Balzani and Venturi recommend emphasising the relevance of chemistry to students, but this is hardly unorthodox (Stuckey & Eilks, 2014). They rely heavily on metaphors and analogies, which again is very common in teaching science (Harrison & Coll, 2008). In particular they draw upon an analogy of chemistry and language. This is not entirely original (for example there is a series of undergraduate texts based on the premise that learning organic chemistry should be treated as aquiring a new language, Holman, 2004), although Balzani and Venturi develop their version of the analogy in some detail.

Balzani and Venturi suggest that some chemical subject matter to be taught should be simplified for school age learners, which might be considered a *sine qua non* of teaching complex technical material at school level (Taber, 2000), and so hardly comes across as anything other than orthodox pedagogy. However, in their presentation of chemistry Balzani and Venturi also adopt (or at least imply) extra-scientific values reflecting particular metaphysical commitments, which can certainly be seen as somewhat unorthodox when science teachers are normally expected to adopt a neutral stance on social and religious questions during their teaching (so that learners do not conflate the science being taught with the teacher's personal viewpoint). Each of these areas will be considered.

Making space for enquiry in the school chemistry curriculum

Balzani and Venturi argue for a chemistry education that is not about simply asking students to learn as much chemistry as possible. Rather they suggest the chemistry that is taught should be that which is shown to be relevant to the lives of students. This is hardly a novel suggestion, and indeed within the chemical education community there is considerable scholarship on how relevance should be understood in school chemistry (Eilks & Hofstein, 2015). Balzani and Venturi suggest that focusing on what can be shown to be relevant will engage students, and leave more space for teaching through enquiry.

Balzani and Venturi rightly recognise that many key issues that are most relevant to modern societies are interdisciplinary and suggest that "by their very interdisciplinary nature, the arguments to tackle are those that lend themselves to lectures in the presence of professors from other disciplines so these questions can be debated" (p.100). This may be something to aspire to, but most schools are not organised or resourced to allow classes to regularly be taught by a team of teachers, so such a recommendation requires some logistical consideration before it could be taken seriously in most schools.

The reference here to lectures might be very disheartening to readers who are actually school teachers or chemistry educators, as lecturing students at school level will in most cases limit learning and deter interest in the subject. However this may just be a misjudged translation as actually Balzani and Venturi also argue for chemistry teaching with teacher demonstrations, student practicals and enquiry work,

> [A]s well, chemical reactions that are accompanied by spectacular manifestations (gas evolution, precipitates and color changes) lend themselves nicely to class demonstrations. They can stimulate the students' interest and confirm that chemistry is, after all, an experimental science (p.98).

It might be considered this is a somewhat defensive and atheoretical approach to teaching chemistry (i.e., use the spectacular to keep the students entertained). That chemistry does offer some spectacular demonstrations is certainly a positive for the teacher, but they should be used as and when relevant to the topics being taught (Taber, 2015b). It is also unclear why such demonstrations say anything about chemistry as an *experimental* subject. If demonstrations are being chosen to be spectacular, then clearly their outcomes are already known, and there is nothing 'experimental' about them. Still, Balzani and Venturi do also favour student practical work:

> [T]he study of chemistry from a textbook may seem interesting to a motivated student. However, to see chemistry *in action* and have hands-on experience through appropriate experiments would certainly be more fascinating and stimulating, particularly to lesser motivated students. Using this teaching approach, commonly called *laboratory education*, allows the student to enter the true world of chemistry and appreciate its appeal and the satisfaction that comes with doing research. (p.101)

Again there is nothing new here to those who work in school chemistry. This reflects, for example, the approach to school science recommended by Armstrong well over a century ago (Jenkins, 1979). Enquiry-based science education (Alsop & Bowen, 2009; Lawson, 2010; Schwab & Brandwein, 1962) is currently a very active theme of science education discourse, and Balzani and Venturi take a strong view on the appropriate balance in chemistry education between acquiring chemical knowledge and developing skills: "the hands-on inquiry-based method…is an approach that, with well-established methods of research and problem solving, focuses on acquiring knowledge and proficiency, rather than a multitude of facts" (p.102). Much of the debate in the science education community concerns the extent to which, to be effective, student enquiry needs to be scaffolded and guided by teacher input (Taber, 2011a). Balzani and Venturi seem to favour open-ended enquiry:

> [A]s was elegantly stated by an old maxim - *one learns through mistakes*. This, however, is true only if the student is not forced to duplicate a procedure given by the instructor. Rather, he devises the experiment autonomously, so as to experience personally the pleasure of experimentation (p.103).

School chemistry *should* give students an effective flavour of doing real scientific research: but of course professional science is done by those who already have a great deal of knowledge and have undergone much skill development; *and* who have the time to face the necessary frustrations of wrong avenues and dead-ends in their research; *and* who are resourced accordingly.

It is important that school students do come to appreciate that real science is not following existing recipes, but it is equally important that they are facilitated to succeed in their enquiries - not immediately, not easily, not even always, but certainly enough to get some real satisfaction from their engagement in the work. Novice enquiry that is too open-ended, certainly when it becomes the norm, opens science teachers to criticisms of not actually teaching (Cromer, 1997), as students are unlikely to make much progress in their learning. Indeed this was a criticism which was made over a Century ago when some science teachers were considered to have adopted too much of a laissez-faire approach to student practical work (Jenkins, 1979).

School chemistry does not offer the luxury of class time, consumables budget, or exemptions from a proper duty of care in health and safety, that would allow students to spend too much of their limited curriculum time learning directly from their laboratory mistakes. So Balzani and Venturi are right to put an emphasis on enquiry in school chemistry, but this has to be structured according to the degree of scaffolding needed for novice chemists to engage in learning activities that will be genuinely educative for them. That is, learners need to be challenged - but also need suitable support to allow them to face those challenges (Taber, 2015c).

Emphasising the everyday relevance of chemistry

One aspect of this book which is done well is the selling of the relevance of chemistry. Arguably this is not actually a major issue with 'many' (to borrow the authors' suitably vague term) students. Most of those who study chemistry in school science can see it has real relevance to food, textiles, fuels, medicines, industry and so on. Many also recognise some of the wonder of the subject - even if perhaps chemistry does not always offer the scale of wonder of astrophysics or the readily perceivable beauty of so much of the biota studied in biology - the compound eyes of insects, butterfly wing patterns, the geometry of snail shells, the symmetry of many flowers, the sycamore seed being dispersed through a mechanism that we might fancy could have been designed by da Vinci, the apparently synchronised movements (murmuration) of flocks of birds, and so on. Chemistry, however, also has its beauty - as well as its drama of smells and bangs and sudden colour changes.

Certainly the theoretical apparatus of the subject – the molecular level models and the thermodynamic calculations for example – offers less appeal to *most* students, even if it may offer just the hook to engage 'gifted' learners (Taber, 2015d). So for many school age learners chemistry offers some wonder and opportunities for fun, and is clearly something important enough that some people (often though 'other' people) should study it, but does not actually appeal as a likely basis for a future career. Chemistry is important, and we need chemists, but many school students will decide that is not an aspiration for them personally. That in itself is not necessarily something we should be concerned about - in an ideal world not everyone would seek to become a chemist as society also needs ecologists and physicians and business leaders and electricians and bakers, etc.

In many countries, however, we certainly could do with a higher proportion of young people aiming for a career in chemistry - and support in selling the subject is welcome. Anyone reading this book will certainly be offered a good perspective on just how widely relevant chemistry is to so many aspects of our lives, and so just what a variety of issues and problems chemists can work on. This is a useful message – even if one suspects that the authors will sadly be 'preaching to the converted' in terms of who is likely to decide to read their book. Whether the approach taken by Balzani and Venturi is optimal is less clear. Despite the focus on applications and relevance, the curriculum recommended is still largely framed in terms of disciplinary structure rather than through the kinds of contexts that are considered to engage learners in the relevance of the subject (Bennett et al., 2003). In terms of the authors' espoused intention to aim their book primarily at general readers, one wonders if the contextual hooks need to precede the chemical concepts. For example, Emsley (2010) has written a very engaging book on the importance and relevance of chemistry likely to appeal to this target readership.

Making the unfamiliar familiar

Teaching can be seen as about making the unfamiliar familiar - that is in finding ways to help learners come to feel ownership of knowledge and understanding that had been alien to them. Teachers can use various strategies to make what was unfamiliar become familiar. The demonstrations and hands-on practical work Balzani and Venturi favour certainly make sense when what was unfamiliar is something concrete and accessible and safe to work with. However, in a theoretical subject like chemistry, not everything we wish to teach can be introduced directly this way. The constructivist perspective on learning (Taber, 2014) suggests that learners must build up new knowledge and understanding based upon their existing resources for learning (what they have already experienced, what they already know and understand). So teachers also use strategies (such as analogies, metaphors and similes) to bridge from what (for the learner) is already familiar to what it is intended should become familiar.

The subtitle of this book, 'Reading and writing the book of nature', refers to a key metaphor developed into a teaching analogy adopted in the text. Nick Serpone (who translated the volume) offers a foreword to the book which claims that "without the rigour of college chemistry, the authors have succeeded in explaining [the concepts of this branch of science] in very simple terms using the language of chemistry, and most interestingly make the unusual association with the language of letters and words" (p.vi). In the preface to their book Balzani and Venturi tell their readers that "chemistry allows us to understand the many things that Nature provides in her book, which the chemist reads and considers adding chapters to; many of these have yet to be written" (p.vii) So Nature is (metaphorically) a book, that chemists are able - through their science - to read.

A theological allusion

Seeing nature as a book seems to reflect the well-established tradition of Christian-inspired natural theology that nature could be 'read' (Lucas, 2005). The assumption underpinning natural theology was that God had provided humankind with two complementary accounts of his works. God had created people 'in His image', which was understood to mean that God had given humans the facility to have some true, if perhaps not full, understanding of the nature of God's creation. Thus a Christian should study nature (as well as scripture) to know the works of the creator God. Some early scientists who adopted this commitment were not beyond referring to God in their scientific writings, before it became generally accepted that natural science should not admit supernatural hypotheses and so reference to a deity was not seen as appropriate as part of scientific accounts of the world.

Although modern scientists are drawn from diverse cultural and faith backgrounds (including theists, agnostics and atheists of various flavours), the issue of how science and religions may be seen as related (or not) is an active one, and one which has major repercussions for science education (Long, 2011; Reiss, 2009). The contemporary 'intelligent design' (ID) movement (that argues that the complexity of life implies direction by deliberate intelligent input) has in the United States been denied the right to have its position included in school science because it suggests that there cannot be a fully natural explanation of evolution. That is, ID does not simply suggest that a supernatural or spiritual layer of explanation may exist alongside the scientific account (something many scientists would accept), but rather that the mechanisms by which life formed are not fully natural and so additional supernatural forces must be invoked. ID argues that *in principle* science cannot offer a full naturalistic account of the origins of life.

A small but vocal group of scientists has attempted to move beyond the widely accepted scientific norm that such supernatural causes are inadmissible in scientific explanations to argue that a scientific worldview somehow excludes the possibility of anything supernatural. Such scientistic views are contested[1)] but support arguments such as: (i) science is the study of the natural world; (ii) as science concerns natural mechanisms, there is no place for supernatural causes; (iii) science therefore excludes supernatural causes and therefore scientists should reject God and other supernatural beings.

This logic only works of course if one accepts that everything can be explained by science, and therefore in terms of natural mechanisms. Where once 'God of the gaps' arguments were commonly adopted (i.e., God explains the bits science cannot, as in the ID perspective), it is more common today for theologians and many scientists to accept that natural explanations are the realm of science but that science cannot provide answers to ultimate questions about purpose and meaning in life and indeed the ultimate origin of the natural realm (Gould, 2001). For example, the Christian notion of the creation implies that the universe is sustained by God who is the origin of all things - including the entities and laws studied by scientists. Even if the big bang might one day be accepted as a natural outcome of some precursor natural event (the collapse of a previous universe perhaps) this does not explain why a natural realm exists in the first place to host such a succession of universes. Ultimately any natural explanation leaves room for a deeper metaphysical level of explanation. This consideration of theological issues may seem a little peripheral to the topic of the reviewed book, but, as will be discussed, there are some odd suggestions and claims in Balzani and Venturi's account of chemistry which can be read as hinting at the presence of 'design' in nature.

The analogy between chemistry and written communication

Balzani and Venturi adopt the notion of reading the book of nature, but consider not only that this book can be read by chemists, but also that chemists are able to add their own chapters. If the book of nature is the work of God, it has been updated to a blog that chemists can post their own comments and replies on – or maybe a Wiki that chemists can edit and add their own pages to. Perhaps this is being fanciful in response to what is simply offered as an analogy, yet when the analogy is presented as so fundamental to the pedagogic approach being adopted by the authors it seems to invite some critical exploration.

Balzani and Venturi put particular stress on the activity of adding to the book of nature suggesting that "the creativity of chemists began when, as explorers of Nature, they became inventors – that is, when they began to synthesize molecules in the laboratory that did not exist in Nature" (p.78). Yet all science involves mental creativity (Taber, 2011b). All the laws and concepts and models and principles of chemistry are mental constructions, and as such the creative output of chemists' minds (this is necessarily true regardless of the extent to which such conceptual tools correspond to the reality of how the world actually is). Any chemical enquiry involves the creative process of imagining possibilities – ways that nature might be - and then creating an experimental design to test those creations. To suggest otherwise does chemistry and chemists a disservice, and undersells the creativity and excitement of scientific work.

Beall (1999) described the language metaphor (and in particular the version where "a letter is the metaphor for a single amino acid residue in a protein; a word corresponds to the secondary protein structure; and so on, up to a complete book, which corresponds to the entire cell") as one of the 'ubiquitous metaphors of chemistry teaching'. Beall warned that "this metaphor is so attractive that it colors thinking about these subjects and if carried too far can lead to erroneous impressions". Balzani and Venturi move beyond metaphor (simply suggesting one thing 'is' another, as a way of implying a similarity) to an explicit analogy.

Analogies imply some structural isomorphism that can be mapped (Gentner, 1983). So if an atom is like the solar system (considering one simple model of the atom), the nucleus is like the sun which has much of the mass and is at the centre, electrons are like planets which orbit, and so on. However analogies usually have negative aspects - things that do not map across in the same relationship. So electrons are all the same, unlike planets, and the centripetal force that leads to their orbit is due to electromagnetic not gravitational force. The presence of negative features - which can usually be found in any teaching analogy – is not a reason to reject the analogy. However, it is recommended that when using analogies as teaching tools the teacher should explore with students both the positive and negative features of the analogy, to ensure the student has picked up the intended comparison and does not import other irrelevant aspects of the analogue to the target concept (Taber, 2013b).

Balzani and Venturi explain that "every language is based on elementary graphical units that we call letters" (p. 16) and that "in a language, letters of the alphabet are generally not used in isolation, but are arranged in groups, following a logic invented by man" (p.16). This seems to refer to written language, although most human languages were originally oral where phonemes or morphemes were surely the more fundamental units, and letters (graphemes) were primarily introduced later to represent what was being spoken. Balzani and Venturi suggest atoms and molecules stand in a similar relation to letters and words:

> [A] *word* is more than just the letters that constitute it. Likewise, a molecule is much more than the atoms from which it is formed. By themselves, the components cannot determine completely the properties of the combinations (p.18).

The properties of a molecule do depend upon the combination and arrangement of the atoms from which it is considered (sic, see below) to be comprised. However, this is not really the case with the language analogue. Usually words are assigned meaning independently of the letters used to spell them. In a language such as English, the combination and sequence of letters does not always clearly determine pronunciation, let alone meaning. The relationship between the key properties of a word and the letters from which it is comprised is often somewhat arbitrary. Where in chemistry molecules with similar composition and structure are likely to have similar properties, that is not necessarily so with words. Balzani and Venturi argue that:

> [T]he relationship between chemistry and language permits a comparison of the atoms with the letters of the alphabet, and the molecules with the words. Just as the words serve to construct sentences that express ideas, so too are molecules the fundamental components whose combination gives rise to the complex world that is in us and around us (p.95).

From a scientific perspective, a negative feature of this extended analogy which we might wish to raise in teaching, is the important difference between how words come to be constructed into sentences and how molecules combine to give greater complexity. The construction of sentences is undertaken deliberately with a specific aim of communicating a particular meaning, and through the conscious agency of a communicator. The complexity of the material world – at least from a scientific perspective – does not derive from a planned process, but is the outcome of natural forces acting on the effectively random movement of molecules – a process which is relatively haphazard. Molecular collisions and radiation are constantly undoing most of the chance syntheses of more complex molecules.

If judged, inappropriately, in teleological terms of success in leading to more complex products, then this process is very slow and wasteful. This is quite unlike the way words are selected and sequenced by a language user. That is, unless one admits a sense of design that considers the synthesis of complexity in nature to be guided in some way. Whether or not Balzani and Venturi ascribe to some form of ID at work in nature, their teaching analogy could certainly be read that way when the negative aspects of the analogy are not made explicit to learners.

Metaphors and analogies in science teaching

There is of course a long tradition of metaphor and analogy in science (Petruccioli, 1993) and in science education (Niebert et al., 2012). The use of metaphor can be seen as intended as a means to aid clear communication of ideas that are expected to be unfamiliar. However, metaphors remain alive (metaphorically) only as long as they are understood to be metaphorical. Continuous exposure to metaphors leads to them losing their metaphorical power. 'Dead' metaphors are just taken-for-granted, so used without being noticed (often by both communicator and communicatee), and in effect over time become literal use of language (Lakoff, 1987). Yet that can actually distort communication if what was meant metaphorically now becomes taken as literal.

One example is that as electrons have angular momentum, they are said to have spin. Now it is generally just accepted that electrons do 'have spin' (a property), leading many students – making sense of teaching in terms of what is familiar to them - to assume that 'electrons spin' (an action). Yet electrons do not 'have spin' because they spin - they are not ontologically the kind of entity that can spin, at least as the term is normally understood in everyday life (that is, they do not have parts that rotate around some central point) - but rather because the term spin has now habitually been extended to quanticles with inherent angular momentum.

The pedagogical limitations of the 'sharing' metaphor

In a similar way, it is habitual to talk of covalent bonding as the 'sharing' of electrons between atoms, as though atoms are the kind of entities that can own electrons, and enter into social arrangements about them. Such talk may seem harmless enough, but students often adopt it as the basis for what they assume are scientifically appropriate explanations in chemistry (Taber & Adbo, 2013; Taber & Watts, 1996). For some students, homolytic bond fission naturally involves electrons returning to their 'own' atoms when the social contract is ended – after all (I have been told) it would seem odd for an atom to end up with another atom's electron. I have even had students suggest that in precipitation ('double decomposition') reactions, the anions would 'return' to the cations 'their' electrons to become neutral atoms, before going on to form ionic bonds in the new compound.

This notion seems to be encouraged by (i) the idea that electrons *belong* to specific atoms; (ii) the priority students give to atoms as species (often assuming all reactions should be considered in terms of reacting atoms, even though very few of the substances they ever come across actually exist as discrete atoms); and (iii) the common alternative conception that ionic bonding is a transfer of electrons (Taber, 1998). So rather than understanding a precipitation reaction in terms of a very simple mechanism of the coming together of existing, oppositely charged ions, students may concoct a more complicated narrative involving electron transfer from existing anions to cations to give neutral species, that *then* form ionic bonds by further electron transfer between new partners. Of course much chemistry is theoretical and abstract and this is challenging for learners - yet here it is not that students cannot cope with visualising and conceiving mechanisms at the molecular level, but rather that they often base their conceptualisations on social analogies rather than more scientific narratives (such as the actions of forces).

Balzani and Venturi tell their readers that "the bond between two atoms – that is, the *glue* that keeps them together – originates from the sharing of a couple of electrons" (p.24). The use of the 'sharing' metaphor here is associated with another metaphor, that a bond is glue. So the "bond between two atoms" is referred to as "the glue that keeps them together" (i.e., using an analogy with everyday macroscopic experience) and this is 'explained' in terms of electrons being shared (i.e., using an analogy with social arrangements). Having referred to the 'sharing' the text moves on without further elucidation of what sharing might mean in relation to electrons and atoms. It seems an explicit metaphor (the bond as glue) is meant to be explained in terms of a dead metaphor (the bond as sharing). That is, the sharing metaphor has become so familiar, so taken for granted, that the authors consider explaining bonding as electron 'sharing' amounts to "demystifying chemistry". Later in the book they refer to "the tendency of the atoms to share their odd electrons" (p.96), but they leave their readers to deduce what this might mean, presumably because they use the sharing metaphor so habitually themselves that it does not occur to them that it may not be obvious to a novice just what is meant to be understood by an atom tending to 'share' electrons.

Magic and molecular recognition

Balzani and Venturi use a variety of other metaphors, similes and analogies in their book. They refer, for example, to the 'birth' of the Periodic Table, something which they considered “was one of the most brilliant coups de force of the last ten centuries”, and which they consider “has been treated as nothing short of magical” (p.13). This is a comparison which surely deserved some development. Magic concerns forms of influence that are outside of scientific explanation (Rosengren et al., 2000). The periodic table is an immensely useful organising scheme in chemistry, but is certainly not magical. Of course, Balzani and Venturi do not state that the periodic table *is* magical, or even that *they* once considered it so, as “the reasons for the similarities between the various elements are now well known” (p.13), but from a pedagogic perspective an important teaching point has perhaps been missed here.

Balzani and Venturi inform readers that DNA “is like the scale of a snail whose handrail is made up of the sugar and phosphate moieties and whose steps are formed by two complementary bases, one for each filament” (p.59). The usual analogy here is a spiral staircase (which might indeed have steps and a handrail), so perhaps there is a mistranslation here (helical staircase, cf. helix as a genus of snails). Indeed in reading the book, there are many places where the reader might wonder if nuances have been lost or shifted through the process of translation. For example, Balzani and Venturi refer to “ammonium chloride (NH_4Cl), which is often used as yeast” (p.46), which seems a bizarre statement. Yeast is a living organism that is used in food preparation because of its metabolic activity, and ammonium chloride would not substitute for this. However, ammonium chloride is commonly used as part of the nutrient medium providing the yeast with a source of nitrogen. Another odd example occurs where the text reports that “chemists have already added tens of millions of artificial molecules to the large number of molecules that exist in Nature” (p.74). One assumes this should have read something like ‘tens of millions of *types of* artificial molecules’, else the claim is a very great many orders of magnitude understated. Finding what seem like clear examples of translation problems undermines the degree to which the text can be assumed to reflect the clear intentions of the authors.

Balzani and Venturi discuss olfaction in the following terms:

> [W]hen the molecules released by the rose reach the nostrils, they encounter nasal receptors in the mucous cavities. These receptors consist of molecules that possess appropriate shapes and properties, such that they can recognize the molecules of the rose by combining with them in a manner reminiscent of a lock and key (p. 9).

The lock and key analogy is of course widely used in discussing biologically important molecules - for example, in terms of enzymes and their substrates. This is a useful comparison, as far as it goes, but like most such analogies needs some unpacking. A lock and key mechanism is not normally spontaneous – it normally requires someone to insert the key, and then turn it to activate the lock. In many ways the action of enzymes and substrates is much more than this, as the ‘mechanism' is automatic. Moreover, a key and lock implies matching shapes, where in the biological analogue the conformation of the molecules may actually change in the process of bonding together: the typical lock has many fewer degrees of freedom. This may seem a little pedantic, but again good pedagogy when using analogies as teaching tools requires the teacher (or author) to explore both the positive and negative features of the analogy.

Balzani and Venturi correctly suggest that chemistry education should not be about learning lots of facts, but rather understanding. Critical thinking is a key aspect of scientific practice, and we should want students to question what they are taught: for example, perhaps to ask in what sense can we say the receptors 'recognise' (another dead metaphor in this context?) molecules from a rose? This particular metaphor is also used elsewhere in the text (see below).

As far as this reviewer was aware, scientists still consider the functioning of the sense of smell at the molecular level to be uncertain. Balzani and Venturi are right that science learning should not be about acquiring facts, for science itself is not simply about accumulating facts, but rather building up theoretical knowledge that can be applied to develop explanations and predictions. Presenting an uncertain scientific theory as fact ("receptors...recognize the molecules of the rose by combining with them in a manner reminiscent of a lock and key") missed an opportunity to offer an authentic representation of the nature of science – that there may be extended periods where there are several co-existing theories, none of which are sufficiently supported by evidence to allow scientists to come to a (technically provisional but) consensual answer to a question. Arguably, one aspect of school science which works against greater student engagement is presenting science as an immense depository of finished investigations (Schwab & Brandwein, 1962). Adopting the use of simile, one might argue that science is not so much like a warehouse of completed studies, as an ongoing journey of discovery where the scientists of today build upon and develop – and sometimes relinquish – the provisional interpretations and understandings of the past. Arguably it is more engaging for learners to know there are several ideas about how olfaction works under active consideration and that scientists are still in the process of exploring the issue. Teaching science as enquiry, which Balzani and Venturi favour, should not be limited to practical laboratory activities.

Seeking the optimal level of simplification in school chemistry

It is well recognised that the abstract and theoretical nature of chemistry is a challenge for many learners (Johnstone, 1982), although perhaps also something that by its nature is likely to appeal to many gifted learners. The phenomena of chemistry are explained in terms of a theoretical description (using terms such as oxidation) and models of matter at the submicroscopic level (such as changes in molecules and the like). That is, learning chemistry generally involves taking on board two complementary and quite different re-descriptions of the actual phenomena, such as colour changes, experienced. So teaching chemistry usually involves helping learners to both reconceptualise what they perceive in terms of abstract theoretical concepts and categories, and also to adopt another level of description and explanation relying upon being able to visualise a parallel level of activity in the unseen, conjectured, molecular realm (Taber, 2013c).

It was suggested above that teaching is the business of making the unfamiliar familiar. One way to do this is by showing learners what has previously been unfamiliar. We can show our students flame colours, for example, or the golden shower obtained when lead iodide is precipitated on mixing a solution of lead nitrate with a solution of potassium iodide. However, the theoretical entities and processes drawn upon in the explanations (electron movements and energy absorbed and emitted by atoms, ions and molecules; the clumping together of a great many previously solvated ions to form a particle large enough to be visible and to settle from solution) – can *not* be directly shown to them. We cannot show a student oxidation or displacement or nucleophillic substitution or polymerisation. We can only show them chemical phenomena that we wish them to learn to conceptualise in these ways.

However, given the nature of conceptual development (Vygotsky, 1934/1994), the expert chemist has developed 'melded' conceptions (Taber, 2013d) where the learnt theoretical interpretations are automatically part of how they actually perceive chemical phenomena. Teachers who have learnt to habitually 'see' the phenomena in terms of the theoretical descriptions and models, such that perception automatically activates the associated concepts, need to deliberately bracket off the theoretical layers to see phenomena from the learner's resolution if they are to effectively scaffold student learning.

The constructivist perspective on teaching suggests that learning is an incremental process of interpreting new experience in terms of established thinking (Taber, 2014), and so teaching needs to find ways to 'anchor' abstract ideas in terms of similarities with what is already known in order to 'plant' the 'seeds' for the growth of new concepts. One way of doing this that Balzani and Venturi draw upon, as has been discussed above, is to use metaphor, simile and analogy to suggest what is abstract (and so perhaps seems obscure or threatening to some learners) is actually just like – or, at least, a bit like – something we already feel we understand well. This is a technique commonly used formally in pedagogy, but is of course widely used in human communication generally, as perhaps when writing about learning in terms of anchors and seeds.

Another pedagogic strategy is to simplify, so where scientific models are complex and nuanced, they may be represented in the curriculum by simplified versions (curricular models), and then during teaching these models are sometimes simplified further still (to produce teaching models) where this is considered necessary to ensure they make sense to particular groups of learners. Yet there is always a balance between making unfamiliar ideas accessible to learners, and retaining the essence of the scientific concepts (Taber, 2000).

Avoiding theory over-simplifies and undermines chemistry as a science

Balzani and Venturi argue that "oxidation-reduction reactions should be discussed in as simple a manner as possible limiting, to the maximal extent, the theoretical part so as to emphasize their relevance in the natural world and in the various fields of human activities" (p.98). However oxidation-reduction is not a concept that reflects some clear class of phenomena in nature, but rather is *by its nature* a theoretical notion that has been invented by chemists and subsequently modified to increase its utility value as the discipline has itself evolved. If limiting the 'theoretical part' implies not discussing redox in terms of formal oxidation states, then this either means excluding discussion of many redox reactions or simply asking students to rote learn them as being redox reactions without any explanation. As with many aspects of Balzani and Venturi's pedagogic programme, the text here lacks enough exemplification to be useful to the teacher in understanding how (following their recommendations) progression in learning chemistry can occur across the school grades.

From an educational perspective, a reasonable understanding of a simplified account – providing it is considered an authentic simplification (Bruner, 1960) – may be a sensible compromise when it is considered that target knowledge represents too great a 'learning demand' (Leach & Scott, 2002) in relation to the learners' prior knowledge. A fair understanding of an incomplete and simplified version of a scientific model is clearly a better educational outcome than complete bewilderment and potential alienation from the subject or class. It is important, however, that the incomplete and simplified account is a suitable basis for developing more sophisticated understanding later, else over-simplification can itself act as an impediment to further learning (Taber, 2001a).

Balzani and Venturi tell their readers, following generations of textbook authors, that "the smallest particle of an element is its *atom* (from the Greek word: *atomos*, meaning not divisible)" p. 13. This is almost part of the traditional creed of chemistry, but if we are wishing to encourage critical thought we might hope a student would challenge this point and enquire '*in what sense* is the smallest particle of oxygen (for example) an oxygen atom?'

The smallest particle of oxygen that might be considered to independently show some of the properties of the element oxygen is not an atom but the oxygen molecule. Theoretically we might expect a pure sample of oxygen to contain minute amounts of some other species - perhaps a very low frequency of ozone molecules or oxygen ions – due to various equilibria. However, to a 'first approximation' we can reasonably ignore these. Considering the oxygen *molecule* "the smallest particle of [this] element" would seem a more reasonable simplification: although even here there is a pedagogical risk of generalisation to all elements – metals are neither atomic nor molecular in nature.

The oxygen molecule (i.e. dioxygen) will be the smallest particle we would expect to find in a sample of oxygen if we exclude low frequency entities, and do not intervene with the sample – for example by shining radiation that might leave to bond cleavage – on it. Of course the molecule is not the smallest particle it is possible to find *under any circumstances* in a sample of the element oxygen, as an oxygen nucleus is smaller, and a single proton from a nucleus smaller still, and a single quark from the proton even smaller. An oxygen atom is also smaller than a molecule, but oxygen does not normally exist as isolated atoms, any more than it exists as plasma or a cloud of quarks. There are certainly conditions where the molecules can be atomised – but then there are conditions when the atoms themselves can be ionised or further decomposed as well. So, despite the familiar nature of the creed that "the smallest particle of an element is its atom", it is difficult to justify such a statement if it is intended to be a naturalistic description of how the world is.

Some elements do have monatomic molecules, i.e. the noble gases, but the vast majority of elements do not naturally occur as discreet atoms. Atoms are not basic units of chemistry in nature, however they are basic units in the ways chemists and students tend to conceptualise much chemistry. So Balzani and Venturi refer to Dalton's model, that "compounds are obtained through a combination of atoms of various elements according to well-defined numerical relationships" (p.20). We now know of course that even though we can certainly conceptualise chemistry this way, compounds are very rarely actually formed from reactants in atomic form. Yet we commonly encourage learners to think in these terms, and when students do so, and do so uncritically, they tend to misunderstand key core ideas in chemistry (Taber, 2013e).

Oversimplification can mislead students

Although Balzani and Venturi appear to reject teaching unnecessary theory, the notion that everything is made up of atoms (whilst almost a creed to chemists) is actually a theoretical notion that is part of a particular conceptual scheme which actually offers limited insight into any phenomena that students will meet in the laboratory or their everyday lives. It certainly simplifies the submicroscopic world imagined by chemists (with its simple and complex ions, molecules, adducts, and lattices, and sometimes atoms, etc.) to adopt the atom as a useful conceptual unit, but it is less clear this helps students build up a mental model of the submicroscopic level which supports progression in learning chemistry (Taber, 2003).

The core language metaphor, adopted by Balzani and Venturi and critiqued above, is framed in a way likely to encourage an 'atomic ontology' for thinking about chemistry: "Everything in a language is made up of letters, so too is all matter made up of atoms. … the molecules represent the combinations of atoms, just like the words result from the combination of letters" (p.16). However, this metaphor also relies on another gross, and potentially misleading, simplification: "Molecules, therefore, are the words of chemistry, the words of matter, the words of things around us" (p.18). Well, that may be a reasonable thing to say of *molecular* matter. However, just as matter is not generally atomic in nature, nor is it always molecular.

Again, from a pedagogical perspective, there is good reason to be concerned about this simplification. For example, students often tend to misunderstand ionic bonding in terms of covalent bonding, seeing ionic substances as made up of pseudo-molecules (ion-pairs in the simplest cases) and so developing a mental model which is not only scientifically incorrect but which is unhelpful in understanding the properties of salts (Taber et al., 2012). Introductory teaching which implies that *everything* is molecular is likely to be unhelpful here, again contributing to pedagogic learning impediments.

There are other examples of educationally questionable simplifications (or simply careless phrasing) in the text. Balzani and Venturi consider precipitation reactions as examples of chemical reactions, which is fair enough when considering laboratory examples such as "the classical laboratory experiments, such as the precipitation of silver chloride", but they also include "the precipitation of salt that takes place in saline marches by evaporation of sea water" (p.40) as an example. By itself, the latter would likely normally be considered a physical change. The distinction between chemical and physical change is commonly made in school chemistry, despite this not being a very clear dichotomy. Offering the formation of sodium chloride by evaporation of saline solution as an example of a reaction *without further comment* may confuse or mislead some students.

Oversimplification is simply bad science

The statement that "though being a spontaneous process, combustion does not occur unless it is triggered by an external stimulus" (p.43) seems somewhat dubious, if not actually self-contradictory. Combustion certainly can and sometimes does occur without an external stimulus, and such a statement could encourage students' intuitive expectations that reactions need to be initiated by some kind of external activating agent (Taber & García Franco, 2010). Balzani and Venturi's discussion of the energy changes involved in combustion are also a cause for concern. They refer to "the chemical energy stored in fuels…compounds rich in energy" (p.43). This type of language has been criticised as associated with unfortunate alternative conceptions commonly developed by learners about bonds 'containing' energy (Novick, 1976). It is preferred that a systemic view is taken, whereby the energy levels are associated with the reagents (collectively) compared with products (collectively). It is not that some compounds store or contain energy, but rather that less energy is needed to disrupt the bonds in these compounds (fuel and oxygen) than is released when the bonds in the products are formed.

A similar dubious simplification is reflected in Balzani and Venturi's recommendations about teaching nuclear chemistry:

> [F]or students to understand *nuclear transformations (nuclear reactions)* requires that they be provided with the appropriate information. Once again, explanations should be limited to a few concepts, which point out the notion that reactions between nuclei cause the atoms to be transformed into atoms of different elements. As they do so, they release a considerable amount of energy (p.99).

This ignores endothermic nuclear transformations and suggests that all nuclear reactions are exothermic. If all nuclear transformations did "release a considerable amount of energy" then the world's energy needs could be solved by setting up a cycle with alternating fusion and fission processes. Of course this is not the case. The reason why the fission of heavy nuclei can be a source of power is because these nuclei were forged in endothermic nuclear reactions in the life cycle of some now dead star. Indeed chemists have used endothermic nuclear reactions to produce transuranic elements - in terms of Balzani and Venturi's preferred metaphor, nuclear chemists do not simply write new words into the book of nature, but actually expand its alphabet.

Another simplification is the rather absolute statement that "when the pH is exactly [sic] equal to 7, the concentration of the H_3O^+ ion is equal to the concentration of the the OH^- ion and the solution is said to be neutral (pure water is neutral)" (p.45). This of course depends upon the temperature, as pH relates to the concentration of the hydroxoniun ion, and water dissociates more at higher temperatures. At its freezing point the pH (and pOH) of pure water is not "exactly equal to 7" at all but almost as close to 8 as 7, and at its boiling point the pH (and the pOH) is not "exactly equal to 7" but closer to 6 than 7. The pH of pure water is only "exactly equal to 7" at one particular temperature. Whether these details matter clearly depends upon the level of the students who are intended to learn from the book. Ideally, however, authors and teachers would avoid making definitive statements of fact that are technically inaccurate, as these can act as pedagogic learning impediments later.

Underestimating the learning demand when visualising the molecular realm

Another example of what might be considered a simplification for teaching purposes occurs when Balzani and Venturi suggest that "chemists have shown, for example, that the molecules of ammonia, NH_3, and of methane, CH_4, are not planar but form, respectively, a pyramid and a tetrahedron" (p.32). It is possible this was not intended as a simplification at all but rather another statement of fact. This may be another example of where over-familiarity with the theoretical content of chemistry can blind a teacher or textbook author to the complexity of the points being made from the 'resolution' of the learner's viewpoint given their limited existing understanding. Part of the expert's melded concept (Taber, 2013d) of the methane molecule is its tetrahedral shape - even though a methane molecule is actually a fuzzy, diffuse object with differential 'density' that lacks the definiteness, edges and faces of a solid shape such as a tetrahedron.

Balzani and Venturi recommend the use of molecular models in teaching chemistry (something that is surely already ubiquitous in most national contexts): as "structural formulas [sic] and molecular geometry are clearly of fundamental importance to the interpretation of chemical properties [and] to simplify and make this part more interesting, the use of molecular models is recommended, including visual computer models" (p.96). There are various ways to model molecules such as those of ammonia and methane. We might use balls and sticks, or balls and springs, or we might use contours or scatter diagrams to represent electron density patterns, or we might simply daw the letters representing the elements linked by lines showing bonding. These are all forms of models, way of representing something which is not easily described in everyday terms (because matter at the scale of individual molecules is fundamentally unlike objects familiar from direct human perception). A major challenge of teaching chemistry is helping students see that the molecular level models of matter used by chemists do not describe the familiar on a minute scale, but a nature which is quite different to everyday experience (Taber, 2001b). Matter at the scale of molecules, nuclei, electrons, etc. is not like familiar solid objects with their impenetrability and their discrete edges and surfaces. Quanticles are fuzzy objects that fade in – more like re-entering the earth's atmosphere than landing on its surface.

Whichever of these modelling approaches we use to represent a molecule of ammonia or methane, we do not end up with the shape of a pyramid or tetrahedron. Rather, to 'see' the molecules as this shape we have to follow a particular formalism. So for methane, for example, we have to imagine the relative positions of atomic centres; then ignore the carbon (!); then imagine lines drawn between the hydrogen centres. (That is, we have to ignore the bonds, and draw lines between atomic centres that are not directly bonded - quite the opposite of the usual rules for representing molecules.) Then we have to imagine these lines as the edges of a solid shape, and consider what that solid shape would be. Thus we represent methane as a tetrahedron. That is what we mean in chemistry by saying that methane is tetrahedral or has tetrahedral geometry. Yet this is certainly not the same as saying that a molecule of methane 'forms a tetrahedron'.

From a pedagogical perspective, there are then a number of steps involved in helping the learner to build upon their existing understanding, to appreciate what we actually mean by suggesting that "the molecules of ammonia, NH_3, and of methane, CH_4, ... form, respectively, a pyramid and a tetrahedron". Without taking into account both the learners' own likely starting points (Leach & Scott, 2002), and the kind of scaffolding needed to appreciate a multi-step abstract process of visualisation, we might teach them a fact (the methane molecule is described as tetrahedral) but we will not encourage understanding and "demystify chemistry" as Balzani and Venturi intend.

Which values should be inherent in science teaching

Much in Balzani and Venturi's book (including metaphors and analogies, and over-simplifications that could be misleading when simply stated and not explored) is typical of what might be found in many general interest books on chemistry or more formal chemistry text books, leaving their clam to a 'somewhat unorthodox' approach unconvincing. However, there are some aspects of the book which could indeed be seen as unorthodox and do offer intriguing (or dubious) suggestions for how chemistry should be taught in schools. In particular, some aspects of Balzani and Venturi's approach imply the adoption of particular extra-scientific values.

Shifting beyond teaching facts, or even beyond teaching theories, to engage with the interactions between science and society opens up potential for introducing controversial issues (Levinson, 2011), and for having to steer the science teaching between values systems that are external to science itself (Sadler, 2011). Such extra-scientific values systems might relate to the assumptions underpinning natural theology - the approach to studying nature referred to above, inspired by religious commitments that saw scientific observation as a complement to the study of scripture - or those related to the contrasting views of some vocal contemporary scientists that scientific work should be seen as inherently an atheistic enterprise.

Science as an activity is informed by certain values that must themselves be adopted and committed to as a starting point – i.e. metaphysical commitments. Metaphysical commitments central to science include the belief in an objective reality, which has underlying stability, and which is to some degree open to human investigation and comprehension. Individual scientists additionally bring their own worldview commitments to science, whether this be that the world will be knowable because it has been set up to be so by a creator, or that there is nothing outside of the magisterium of science, because there is no supernatural realm. However, these personal commitments are not inherent to science itself (Taber, 2013f).

Arguably a science teacher *qua* science teacher, has a duty to teach students about the values that underpin science (e.g., always being open to considering new evidence), but not to suggest that science embraces other values and metaphysical commitments that although adopted by *some* scientists, are not inherent in science *per se*. The science teacher *qua* science teacher can certainly share with students her or his personal sense of wonder at the world, but should not suggest to them that – for example – this wonder reflects God's creative power. Equally, the science teacher *qua* science teacher should encourage her or his students to appreciate how science offers the best way to understand natural mechanisms, but should not teach students that there are no valid complementary forms of explanation or understanding beyond science. Science *qua* science is neither theistic nor atheistic and school science should be presented in a balanced way that is equally accepting of students whatever their faith background or cultural worldview.

Conflating personal worldview and scientific commitments

Balzani and Venturi suggest that science needs to be complemented by other ways of knowing:

> [T]here are, in fact, questions that science will never be able to answer. For instance, who made up the laws of Nature? Why are we in this world? What sense does the life of man have in a word of objects? Inasmuch as science cannot answer these questions, man searches for answers in other areas (p.64).

It is noticeable however that their formulation here is not neutral. They suggest the question 'Why are we in this world?' (i.e. what is the reason?) rather than 'are we here in this world for a reason?' They pose the question 'who [sic] made up the laws of Nature?' (i.e. assuming someone did) rather than 'how did the laws of nature arise?'.

When they consider bioethics, Balzani and Venturi argue that in a world where individuals have their genomes mapped:

> [I]f, for example, a gene were responsible for a serious disease that manifests itself after many years, the individual bearers of that gene, beyond having their existence ruined to begin with, would have great difficulties in finding a job. Such bearers would likely spend their lives in complete solitude, without the possibility of having a family and children (p.63).

There are a number of issues here which are oversimplified. A person known to be likely, perhaps even genetically determined, to have a serious disease may find this effects their occupational and personal opportunities. But it seems unlikely such a person would be excluded from working or need to live in complete solitude. That is certainly not the case with people who are currently in this situation. Moreover, we all die eventually, and often suffer years of ill health before that - yet this is not generally considered to negate the value of human life. So to argue that having genes which will lead to serious disease ruins one's very existence is questionable, and might be found quite objectionable by people living with the expectations of developing such conditions. Balzani and Venturi presumably simply wish to raise the ethical issues, and likely do not intend to suggest that the life of a person who has a serious genetic condition *should* be considered of no or little worth, but the wording here could be more sensitive.

Balzani and Venturi do not then follow the usual line that a science teacher should attempt to approach socio-scientific issues as a neutral chair who encourages students to explore different perspectives and make up their own minds on issues. So the reader is told that "the use of nuclear weapons for warlike purposes must certainly be deplored, and it should also be pointed out that nuclear power plants are not the right answer to energy issues for several reasons, including the risks they entail" (p.99). Most teachers would be happy to deplore the use of nuclear weapons - but the situation with nuclear power is much more nuanced. Perhaps nuclear fusion will one day become the preferred source of power in many countries. Even if not, the complexity of the issue is reflected in how one of the scientific gurus of the environmental movement – James Lovelock, the developer of the Gaia theory of the earth (Lovelock, 1979/1987) – favours nuclear power as an environmentally necessary approach.[2)]

Does chemistry suggest humans are special

There are other quirky aspects in Balzani and Venturi's presentation. They draw upon the conundrum that we retain our identity despite constant renewal of our material composition. This is something that will engage many readers (and perhaps spook some). However, Balzani and Venturi go beyond this to make some rather specific claims:

> [E]verything in us is continuously renewed as we draw from matter and energy in our environment. Our skin renews itself every month, our liver every six weeks. Every year, 98% of our body is renewed. Consequently, we can safely say that, in the real world [sic – as compared with?], we are the most recycled species. Even our memories, which are particular structures of the brain, are continuously being dismantled and reassembled through atomic and molecular exchanges (p.40).

The reference to our memories as being structures in the brain that are dismantled and reassembled offers a strong image and is likely to be something that will be found striking by many readers. There are problems with the description offered here though. Our memories are not static, but that is because what is experienced as memory is not identical to the physical substrate that acts as the representation on which memory is based. When we activate those representations we experience memories, and our brain can be simultaneously active in modifying those same representations. In a sense our memories are a by-product of the evolution of an apparatus for interpreting the present and predicting what will happen in the near future, and despite our tendency to see memories as pure accounts of experience, there is no absolute distinction between the ongoing model of reality that is being constantly updated to best fit experience and the 'store' of past experiences (Taber, 2013d). However, this is all to do with how our cognition works, and is not about the maintenance level of replacing damaged materials within the system (which in principle need not change memories at all).

More intriguingly, there is another odd claim included here. The authors present statements about the extent to which the material in our bodies undergo ongoing recycling - and then imply that they have demonstrated ("we can safely say") that "we are the most recycled species". Assuming they mean this claim in a scientific sense (the species = homo sapiens), the argument is very weak as they have offered no comparison to recycling in any other species. Indeed, at first sight, it would seem very unlikely that the material in a human being (much of which is well-protected from the external environment) is recycled at a greater rate than, say, that in an amoeba or bacterium.

Later in the book there is another rather similar slip where the complexity of living cells is discussed, and readers are told:

> [T]he degree of complexity of the human cell is far greater than that of bacterial cells. First of all, the human cell contains a large number of components (more than 100 000 billion molecules), and has, above all else, the highest level of organization (p.57).

It is not clear precisely what comparison is being made here. Bacteria (one of the main groups of living things) are contrasted with humans (one species among many millions) which it is claimed has the "highest" (sic, not higher) level of organisation. Human cells may certainly be much more complex than bacteria cells - but this would be true of cells of any eukaryote species (which likely developed from synthesis of several simpler cell types). There is 'sleight of hand' here, where because human cells are so much more complex than bacterial cells, we are told they have the most complex organisation of any cells. Yet, by this logic, if the explicit comparison had been bacterial cells with pig cells, or with beetle cells, or with grass cells, or with fern cells, or with toadstool cells, or with earthworm cells, then it would be equally possible (and invalid) to suggest that pigs or beetles or grasses or ferns or toadstools or earthworms have cells with the highest level of organisation.

So the authors here offer some interesting ideas about the nature of life from a chemical perspective (likely to engage readers), but sneak in some rather anthropocentric claims about humanity as being somehow special among species. Many people believe humans are special on non-scientific (e.g. religious) grounds, but from a scientific perspective humans are one of a great many species, each unique in some small way. By making noteworthy but dubious scientific claims – humans are the most recycled species, human cells have the highest level of organisation – Balzani and Venturi mark out homo sapiens as some kind of pinnacle of the natural world. This is in marked contrast to the perspective generally taken in science that considers different multicellular species as equally evolved but distinct responses to particular ecological challenges.

Teleological framing of scientific ideas

Balzani and Venturi also tell readers that "as long as the Sun shines in the sky, which will occur for a long time to come, life will continue to exist on Earth" (p.50). This is certainly not consistent with current scientific thinking. After the end of its current fairly stable phase (of largely reacting hydrogen nulcei, thought due to last around another five billion years) it is expected that there will be very substantial changes in the size and brightness of the sun as it becomes a red giant. Indeed well before this, a gradual but substantial increase in solar radiation output is likely to make earth too hot for liquid water to exist. We might expect life to continue on earth for another one or two billion years – but unless current scientific models are *very* wrong or there is a substantial intervention (to cool the sun or shield the earth) life on earth will end long before the sun stops shining. Again it is not clear if Balzani and Venturi have simply got their science wrong, or whether their claim is based on some extra-scientific commitment (to the possibility of future human technological advances; to supernatural intervention?) as they do not explain their reasoning. Rather they simply posit a factual statement to be accepted by readers: albeit one that contradicts current scientific models.

Balzani and Venturi also adopt a way of describing the molecular world which has teleological features (Talanquer, 2007). They refer to how molecules are programmed to recognise each other and build up the compounds needed for life. This goes beyond the type of social anthropomorphism discussed earlier in this review, leading to molecules said to encounter, read, ignore and the like ("when two molecules encounter each other, each molecule reads the information elements contained in the other molecules [sic] and, depending on such components, they either ignore each other, react to produce new species, or else associate to form a supramolecular system", pp.53 – 54), to suggest a sense of pre-planning in nature that seems to reflect intelligent design:

> [m]olecular recognition can be programmed through *codes* based on the specific localization of certain atoms (or groups of atoms), on the shape, and on other electronic/structural features of the molecule. A large number of molecules are present in Nature. They are so programmed [sic] as to undergo association from which originate supramolecular systems involved in processes that lie at the very foundation of the evolution of life (p.56).

This phrasing inevitably raises the question of *who* programmed the molecules to do this.

Overview: a book that exemplifies enthusiasm for chemistry, but offers limited pedagogic insight

In summary it seems necessary to evaluate this book at two different levels - in terms of what the general reader might get from it, and in terms of its contribution to the pedagogy of school chemistry. Where this volume is unquestionably strong is in the shear enthusiasm for the subject matter. Anyone reading this book should come away from it thinking that chemistry is very important, very relevant to their life, and has the potential to be absolutely fascinating. If it seems unlikely that the book will, as Balzani and Venturi seem to hope, convert those bored by school chemistry to enthusiasts for the subject, this is simply because those people will probably not buy or read the book. However, the young reader already interested in school chemistry will surely find much in this slim volume to reinforce and extend that interest.

In many ways it is a shame that Balzani and Venturi did not limit their efforts to such an audience. However, instead they set out their views on how to develop the chemistry curriculum, and how to organise and carry out chemistry teaching. Here they run the risk always faced by experts in one field when tempted to offer their views in another area – that of being seen as misguided amateurs. There is an active field of research in chemistry education, and more widely in science education, where genuine experts undertake serious scholarship and carry out careful research. Of course, not everything written by chemistry education experts is exemplary (any more than is the case in other fields). But here Balzani and Venturi manage to reinvent several wheels that have long ago been carefully invented, tested, critiqued and developed with the support of researchers around the world. Those researchers offer arguments from the literature, and the analysis of evidence from classroom contexts. Balzani and Venturi identify a problem (the apparent lack of enthusiasm for chemistry among the non-chemists they meet), suggest a cause (school chemistry teaching), and go about offering a cure (how chemistry should be taught in schools) without – as far as the reader can tell – talking to a single school teacher, or a school pupil, or actually observing in a school chemistry classroom. They recommend practice, but it is not evidence-based or research-informed practice (Taber, 2013a).

Balzani and Venturi make some sensible suggestions (build models, teach by enquiry, simplify complex ideas, use metaphor and analogy) - but these tend to reflect existing widespread thinking in the field. They also commit some cardinal sins in terms of educational thinking. They do not offer any sense of differentiation across the diversity of learners experiencing school chemistry - so that their approach will not meet the needs of the gifted learner who requires intellectual challenge. They argue for selection of curriculum - but sometimes on the basis of going for the spectacular and omitting the theoretical. That will get short-term gains in student interest - but chemistry is a science, a discipline where there is constant interplay between theory and observation. Reduce theory too much and what is left is not science and so is not really chemistry (and arguably does not actually justify a place in the compulsory school curriculum).

Simplification is inherent in teaching school chemistry – but the simplification has to be principled, and seen as part of a spiral curriculum (Bruner, 1960) that supports progression in chemical learning and thinking (Sevian & Talanquer, 2014). Often Balzani and Venturi argue for simplification for its own sake, and in doing so they are recommending teaching science that is not only simplified, but sometimes just wrong.

Metaphor and analogy are core strategies in science teaching, and are regularly adopted by chemistry teachers – but again this needs to be done carefully as a means of initiating new learning through what is already familiar to learners. The use of analogy in teaching must highlight both positive and negative aspects and should be seen as a first step to teaching scientific accounts. There is little value in students learning metaphors and analogies for their own sake if this limits their understanding to the level of non-scientific slogans (e.g. bonds form because atoms tend to share electrons).

In particular, science education should be limited to the scientific account, with its natural mechanisms and should neither suggest nor deny that there may be some ultimate purpose to the material world or humanity. That is not the concern of science, even though it may quite rightly concern individual scientists, science teachers and their students. From a scientific perspective, humans are one species among many – special in our own way as all species are. From a scientific perspective the evolution of complexity is the outcome of natural processes that can be described in terms of natural laws and which involve the action of natural (blind, non-deliberating) forces.

Balzani and Venturi are to be praised for their commitment to sharing their enthusiasm for chemistry with non-specialists, and for taking an interest in school chemistry education. However, from the perspective of the research field of chemistry education, Balzani and Venturi show a serious lack of expertise in terms of educational thinking, and most of their well-meaning recommendations either reflect what is already commonplace practice or are misguided. Balzani and Venturi suggest that their approach to explaining chemistry is "somewhat unorthodox" (p.vii). Where they are somewhat unorthodox is (a) in ignoring some of the widely accepted principles developed within the field of education for thinking about how to best support the development of student thinking through different stages in their learning, and (b) for offering a formulation which sometimes presents a teleological account of nature, hinting at some inherent designer at work, and making questionable claims about the special nature of homo sapiens in the natural world. That could be considered to be "demystifying chemistry" (p.vii) only by assuming a shared (i.e., with readers) metaphysical commitment to a position on an even greater mystery. That goes beyond the remits of a book that claims to provide understanding of a scientific discipline.

NOTES

1. http://content.time.com/time/printout/0,8816,1555132,00.html
2. http://www.independent.co.uk/voices/commentators/james-lovelock-nuclear-power-is-the-only-green-solution-564446.html

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