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An alternative conceptual framework from chemistry education

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Abstract:

The science education literature includes many claims that learners commonly hold alternative conceptual frameworks about aspects of the science curriculum, especially in physics. There has also been criticism of the general notion of 'alternative frameworks', although some of this would appear to be due to different authors using the same terms in distinct ways. In this paper it is suggested that research evidence provides strong support for the view that many students of chemistry demonstrate similar alternative conceptions about some fundamental aspects of chemistry. These common alternative notions may be shown to be logically connected, and are here considered to together comprise a coherent alternative conceptual framework. Although it is *not* suggested that students will necessarily hold to *all* aspects of the framework, it is considered that the framework is a useful model of alternative thinking that teachers of chemistry should expect to find among their students.

Introduction

Research into learners' ideas in science has led to a vast literature and has included claims that learners exhibit a wide range of alternative conceptions about scientific topics (Carmichael and coworkers 1990-2, Duit 1991, Driver, Squires, Rushworth and Wood-Robinson 1994). Some workers have referred to *alternative frameworks*, and, for example, it has been claimed that physics students commonly demonstrate alternative frameworks for concepts such as energy, force and gravity (e.g. Watts 1982, 1983a, 1983b). Much of this work has been undertaken from within a constructivist frame, which has been well described (Driver 1983, 1989, Driver, Guesne and Tiberghien 1985, Driver and Oldham 1986, Gilbert, Osborne and Fensham 1982, Pope and Gilbert 1983, Pope and Watts 1988, Watts and Pope 1989).

There has been much discussion of the merits of the constructivist position. Criticism has been of a varied nature, but - to give a flavour - Matthews (1993, 1994) objects to the apparent relativism of granting learners' alternative ideas a high status; Millar (1989) accepts constructivist premises but questions assumptions about effective teaching style drawn from them; and Solomon (1993, 1994) criticises the emphasis on *personal* construction of knowledge that has apparently underplayed the *social* context of school learning.

Alternative conceptual frameworks

Of more central importance to the present paper is the question of the general validity of the notion of alternative conceptual frameworks, such as the one proposed below. The idea of alternative frameworks is well established in the literature, particularly since the appearance of two seminal papers published one-and-a-half decades ago (Driver and Erickson 1983, Gilbert and Watts 1983). However this journal has more recently published a paper questioning the existence of such frameworks (Kuiper 1994), and it is therefore appropriate to deal with this dispute.

In 1978 Driver and Easley suggested the term *alternative frameworks* for "the situation in which pupils have developed autonomous frameworks for conceptualising their experience of the physical world" (Driver and Easley 1978, p.62, *italics* in original). Later Driver explained that *conceptual frameworks* were *alternative* in those cases where "the accepted theory may be counter-intuitive with pupils' own beliefs and expectations differing in significant ways from those to be taught" (Driver, 1983, p.3). Pope and Gilbert saw that the notion of 'alternative frameworks' could be related closely to George Kelly's personal construct theory where the "main emphasis is on the uniqueness of each person's construction of the world and the construct systems each will evolve and continue to evolve in order to import meanings of their experiences", and they considered that *alternative frameworks* "would be seen as sensible coherent expressions of this cognitive activity" (Pope and Gilbert 1983, p.197).

Gilbert and Watts highlighted the need to distinguish between "an individual's psychological, personal, knowledge structure" (1983, pp.45-65) - e.g. the 'concept' as inferred to be in the learner's head - and aspects of "the organisation of public knowledge systems", i.e. the orthodox academic version of the 'concept' as presented in textbooks etc. Indeed when discussing learners' ideas in science one needs to distinguish between an individual's cognitive structure (which can only be conjectured), and the researcher's own models (which can be formally represented in words and diagrams). So Ault, Novak and Gowin (1984) are careful to distinguish cognitive structure itself from the representation that is a product of their analysis. They use research data to infer a '*conceptual structure*' that is "a best approximation of cognitive structure, the 'true object' of interest" (p.446). Lakoff and Johnson describe this difference between the "structures through which we categorize personal experiences and external occurrences" and representations "which we … construct as models" of these structures as a "most important distinction" (1980, p.206).

Just as important, however, is the need to distinguish between representations of aspects of an *individual's* cognitive structure, and general models which are intended to reflect *commonalities* from the representations derived from several individuals. In her early writings Driver clearly used the terms 'conceptual framework' and 'alternative framework' to refer to aspects of an individual learner's cognitive structure, that is for "the mental organisation imposed by an individual" (Driver and Erickson 1983, p.39) which was utilised "for conceptualising their experience of the physical world" (Driver and Easley 1978, p.62). In contrast other workers used the same term to refer to their representations of *common features* in their *models* of aspects of the cognitive structures of many individuals:so that a framework may be described as "a composite picture based upon *ideas shared by a number of pupils*" (Watts, Gilbert and Pope 1982, p.15, my emphasis), as "generalised non-individual descriptions" and as "thematic interpretations of data, stylised, mild caricatures of the responses made by students" (Gilbert and Watts 1983, p.69). To summarise this difference, for Driver, the conceptual framework is part of an individual's cognitive structure, something inside the mind of a learner, where for Gilbert and Watts the 'framework' is something presented in the public domain that is constructed by the researcher on the basis of data collected from a sample of learners.

Having established this distinction, it is now appropriate to consider Kuiper's criticism that alternative frameworks do not actually exist. Watts has published results of his research into learners' understanding of the concept of force, *summarising* his results in terms of eight alternative frameworks (1983a). In Kuiper's own study of student ideas about force he failed to support the specific findings of Watts and others, and made a claim that "students in general do not have an 'alternative framework' for force" (1994, p.279). However Kuiper does not take into account that Watts' research was reporting alternative frameworks that were "a simplified description" that came "from no *one* pupil", but had "been pieced together from the implicit and explicit conceptions used by the children" to "form a composite picture based on the ideas shared by a number of pupils" (1983a, p.218).

Pope and Denicolo (1986) had foreseen the dangers of 'frameworks' in the naturalistic research literature being taken out of context by those - like Kuiper - working in a reductionist manner. They explained that authentic reports would describe the subtleties of individual learners' ideas, and the stages of data reduction used in the analysis. However such reports would be too detailed and dense to be read by the teachers to whom they were addressed, and too long to be published in most journals. Thus: "authenticity must be tempered with utility" (p.156). Pope and Denicolo used Watts' work as an example: he had "clearly described his data degradation process as he moved from consideration of [the] child's alternative conceptions, through categorisation of exemplars of these conceptions using verbatim quotes as evidence to the production of descriptions of a range of *alternative conceptual frameworks*" (p.157). They warned that "although starting from a holistic approach *one* 'end product' of his work is a much reduced description of the construing of the individuals in his study which, if taken out of context, is also devoid of consideration of the particular choices made by the researcher in his conduct of data collection and analysis" (p.157, emphasis in original), and suggested that "the busy teacher or researcher with a predilection towards reductionism may well ignore the 'health warnings' conveyed in our research report [and] indulge in a 'framework spotting' exercise using reified descriptions of frameworks and ignoring the ontology of these frameworks" (p.157). Kuiper's study suggests that he has indeed ignored Watts' 'health warnings'.

The term 'framework' has sometimes been used interchangeably with 'conception', so that Driver included in the term *alternative frameworks* both "an idiosyncratic response to a particular task" and "general notions applied to a range of situations" (1983, p.7). The view taken here is that it is useful to draw a distinction between aspects of cognitive structure which influence student behaviour (such as answers to questions) in response to a range of stimuli (such as a series of questions on a topic area), and the level of thinking that produces a single proposition. It has been suggested that "propositions are the 'molecules' from which meaning is built and concepts are the 'atoms' of meaning, to use a rough metaphor" (Novak 1985, p.192). The identification of *conception* with proposition seems to reflect workers such as Hewson for whom "the term conception is used to indicate a functional unit of thought" (1985 p.154), and Strike and Posner who "make no distinction between *conceptions* and *ideas* and use the terms interchangeably" (1985, p.213, italics in original). The term 'framework' suggests 'a basic structure which supports and gives shape' (Watson 1976) and Abimbola uses 'framework' in such a sense, as "the *organization of ideas* rather than the ideas themselves", so that *alternative frameworks* are "just the undergirders that anchor ideas" (1988, p. 181, my emphasis). This is consistent with Ault and coworkers' notion of 'conceptual structures', models of aspects of cognitive structure "likely to *generate*" a student's "claims about events" (Ault, Novak and Gowin 1984, p.446, my emphasis), and with Viennot's approach to investigating *in which* framework elicited student conceptions occur (Viennot 1985, p.433).

My own 'health warnings'

It is from this perspective then that this present paper proposes an alternative framework from chemical education. It is not claimed that the framework *precisely* makes up part of the cognitive structure of any *specific individual* chemistry students. Rather, the framework is a model constructed by the author to represent related aspects of learners' thinking that were elicited during empirical research. The framework is a composite derived from interpretations of the comments of a range of learners:that is it follows Gilbert and Watts' approach of frameworks being "generalised non-individual descriptions" and "stylised, mild caricatures of the responses made by students" (1983, p.69).

Methodology

The framework presented here is grounded in research undertaken with A level chemistry students in a Further Education College in the U.K. The research was based around in-depth interviews undertaken by colearners - students choosing to take part in the project and explore their ideas about chemistry (Taber, 1994a) - at different stages of their two year pre-university course. The interviews were focussed on the key concept of the chemical bond, and were based around decks of figures representing chemical species (Taber, 1997c). 15 students were interviewed over the period January 1991 to May 1994. The interviews were used to prepare detailed case studies of the developing understanding of individual learners (Taber 1995, Taber and Watts in press).

Case studies are not intended to be generalisable, but the principles of 'grounded theory' suggest they may be used as a starting point for developing authentic models of wider relevance. Such models have the advantage of *emerging* from the data, rather than being dependent on predetermined categories used in the research (Glaser 1978). They are also capable of being tested by traditional hypothetico-deductive techniques. The case studies were used as the foundations for developing a grounded theory of A level students' developing understanding of chemical bonding, using 'theoretical sampling' to build on the evidence provided by the interviews with colearners (Taber 1997b). Interview data was supplemented by Kelly's construct repertory test (Taber 1994b), by recording student discussions; and by collecting samples of work - concept maps, answers to examination questions and so forth - from a wider population of A level chemistry students (Taber 1997c).

Results

One outcome of the study was that students were found to commonly use the octet rule - a heuristic for identifying stable chemical species - as the basis of a principle to explain chemical reactions and chemical bonding:the full shells explanatory principle. From this perspective bonding "is done in order to try to achieve a stable structure i.e. 8 electrons in the outer shell of the atom". All of the colearners used the octet rule as an explanatory principle at some point during the interviews, although the phrasing varied considerably ("to give them all full outer shells", "to obtain the configuration of a noble gas, and be stable", "to form a completed outer shell" etc.)

Furthermore this explanatory principle appeared to form the basis of an alternative conceptual framework for understanding chemistry:the octet rule framework. This framework includes notions that are incorrect, but also perceptions that would better be described as *partial* perspectives or *limited* understandings. The various aspects of the octet rule framework will be illustrated with a small sample of representative quotations from the data base (Taber 1997c).

An atomic ontology:atoms as the units of matter - the building block metaphor

The research suggests that atoms are ascribed a special ontological significance by learners, so that chemical systems tend to be conceptualised in terms of combinations of atoms - which are perceived as the 'natural' units of matter (Watts and Taber 1996). The evidence collected suggests that the metaphor of atoms as "the building block of *everything*" may be adopted by learners, without consideration of the ways in which atoms are *not* analogous to building blocks. Students commencing A level often suggested that atoms were indivisible, and "can not be broken down", so that "an atom it is the smallest thing in any mater". No contradiction was apparently perceived in the atom being the "smallest particle that can be found, made up of protons, neutrons and electrons", nor in that "an atom is the simplest structure in chemistry [yet] it contains a nucleus with protons and neutrons, and electrons moving around shells".

Seeing an atom as *the* basic unit means that molecules are seen as combinations of atoms (e.g. "a group of atoms bonded together") rather than as a basic entity, or as a system of atomic nuclei/cores and electrons, and similarly ions are often seen as altered atoms (e.g. "an atom which has lost or gained electrons"), rather than being viewed as entities in their own right (Taber 1996).

The assumption of initial atomicity

Learners may assume that any chemical system they are asked to consider has evolved from discrete atoms. Students setting out on A level chemistry described how:

- the reaction of hydrogen and oxygen "occurs because hydrogen *needs* 1 electron to complete its shell of electrons and oxygen *needs* 2 electrons in order to complete its outer shell, therefore they *share* the electrons in a covalent bond, so that they both have the required number of electrons in their outer shells";
- the combustion of methane occurs because "carbon which has a valency of 4 *requires 4 more electrons* in order to stablaize [sic] its outer shell. Oxygen which has a valency of 6 and *requires 2 more electrons* in order to become stable";
- sodium will react with chlorine because "Sodium has to get rid of an electron to achieve a full outer shell status and Chlorine has to *try* to gain an electron to complete its outer shell".

This same assumption may persist despite studying the A level course. For example, near the end of his course one colearner suggested that hydrogen reacted with sodium "to become *more* stable" because "each hydrogen *atom*" had "just one electron". On further questioning this student acknowledged that the hydrogen electrons were already paired up in the molecules, and he did not think the electrons would unpair. Yet he still could only explain the reaction as occurring because "before when they start, they just have one electron in the outer shell, hydrogen atoms, now when they combine they've got two electrons".

Ownership of electrons

Although the view that an electron *could not exist* outside of an atom was rare in the research, it was common for electrons to be considered to *belong* to atoms. This term was not restricted to electrons in isolated atoms, but rather colearners would commonly identify which electron in a covalent bond *belonged* to which of the bonded atoms.

Covalent bond as sharing of electrons

References to the covalent bond as *sharing* of electrons were ubiquitous. In some cases this notion was viewed as a sufficient explanation of the covalent bond: which was considered to hold atoms together *because* it is sharing of electrons. Indeed the act of sharing was described as being "like a force". Another colearner explained that a molecule was held together by "the two electrons shared" which "makes them more like joined together like one".

Usually the sharing of electrons was related to the full shells explanatory principle, so that "the electrons are shared *to* create a *full outer shell*", and the "covalent bond is the sharing of electrons *to complete full valency shells*". As one student wrote in a test paper,

"A covalent bond is one in which two atoms join together by the sharing of electrons. Each of the atoms achieves noble gas configuration in the process of covalent bonding."

The ionic bond as electron transfer

In the research it was found that ionic bonding was understood as "where you, donate, or gain electrons, *to form a completed outer shell*". The full shells explanatory principle was considered to explain why electrons were transferred to form ions. In the following interview extract it is seen that this is accepted as *sufficient* explanation, I: Why do they form a bond? … Why does the electron get transferred?

Q: Because they want a full outer shell.

I: Why do they 'want a full outer shell'?

Q: To be stable.

I: Why does that make them stable?

• [pause, c.1s]

Q: Erm. Because the outer shells are full.

I: And that makes them stable?

Q: Yeah.

(I:interviewer [KST]; Q:colearner)

The metallic bond

In the present research it was found that at the start of an A level course students were generally only vaguely aware of metallic bonding. The model of metallic bonding presented to the colearners during their A level course was in terms of electrostatic forces. However, the full shells explanatory principle was invoked in the colearners' explanations, so that at the end of her course one colearner described how "metals haven't got full outer shells, then by electrons moving around, they're getting, a full outer shell, but then they're sort of losing it, but then like the next one along will be receiving a full outer shell". Alternatively, another colearner conceptualised metallic bonding as being "formed by the one, two or three valent shell electrons being donated to lattice so a noble gas configuration is achieved".

Stable species

Although colearners tended to think in terms of atoms, they generally did not consider most atoms stable:so for example a sodium atom is not stable "because the outer electron shell is not full, and therefore that electron has to be lost, in order to make, in order to have a, outer shell full". Another colearner went further, and said that a single sodium atom was not stable "because it hasn't got a, a full outer electron shell" and "it's not possible to have one [sodium atom] on its own". This same colearner thought that once an electron had been removed to give the stable ion, it would then not be possible for further electrons to be removed. As another student wrote in an induction exercise,

> "If an atom has been filled up or [is] all ready full up (of 8 outer electrons) it becomes stable and therefore it is unreactive. The atom will stay that way *forever* and not react or loose or gain any electrons."

It was found in the research that most students thought that once an electron was removed from a sodium atom it would not be able to return as there would be a stable electronic configuration. Indeed the power of the full shells explanatory principle was such that most students surveyed thought that a sodium-seven-minus ion (Na^{7-}) with an electronic configuration of 2.8.8 would be more stable than a sodium atom (Taber 1997c).

Use of anthropomorphic language

In the research it was very common for students to speak of atoms as if they were sentient actors in the molecular soap-opera of chemistry (Taber and Watts, 1996). Ignoring terms such as 'shared' 'donated' and 'accepted' which when applied to electrons might be considered dead metaphors (i.e. terms that had originally been meant metaphorically, but with common usage have come to take on a new literal meaning), there were many suggestions that atoms *wanted* or *needed* to gain or lose electrons. Indeed this usage was ubiquitous in student comments, although alternatives included atoms preferring, liking, being eager, or having no wish for certain outcomes. When hydrogen bonding in hydrogen fluorine was considered one colearner accused the fluorine of being *greedy* for "*trying* to grab two electrons" from different hydrogen atoms.

The full shells explanatory principle is inherently anthropomorphic, as no physical force is invoked to explain why systems should evolve toward certain electronic configurations. Rather, it was assumed that this was what atoms want, and they act accordingly: "in all cases what an atom is *trying* to do is become stable". Awareness was invoked, with learners suggesting that dimers of aluminium chloride formed so that the aluminium atoms would "think" that they had the octets they needed to be stable. Another colearner referred to an atom that "would want to" lose an electron, but otherwise would still be "happy".

The significance of electronic history

It was found in the research that students commonly assign significance to the personal history of species such as electrons. Learners suggested that on covalent bond fission the electrons returned to “their own” atoms. As one of the students explained “it would seem a bit of an odd-ball” for one atom to have another atom’s electron. When this reasoning was explored it was found that some students thought that the force between nucleus and electron only applied to (or was greater for) the atom’s “own” electron.

The importance of an electron’s biography was also seen in the case of ionic bonding, where the bond was usually seen as the transfer of an electron. An ionic bond was *only* considered to exist between ions where such transfer had occurred, not between other counter-ion pairs. When shown a diagram representing a layer of ions in sodium chloride students would quite confidently suggest where electrons had been transferred and so which of the adjacent ions were - according to this criterion - bonded. Some students actually considered the transferred electron as a kind of loan, so that the electron would be returned to its own atom should the ion-pair be separated. (As, for example, in a double decomposition reaction when the original ions may be considered to change back to atoms, so that a new electron transfer event can occur to provide an ionic bond between the species forming the precipitate.)

References to ionic molecules

Because of the significance granted to electronic history the ion-pairs considered to have been involved in an electron transfer event were perceived to be like discrete molecules within an ionic lattice (Taber 1994c). It was quite common for students to refer to molecules of sodium chloride.

Electrovalency as the determinant of the number of ionic bonds formed

Another consequence was to deduce that an atom could only form ionic bonds with a number of counter-ions equal to its electrovalency, just as the covalency determines the number of covalent bonds formed. The argument ran that bond formation occurred to obtain a full shell, so that an atom that only needed to gain/lose n electrons would only form n bonds. So one student suggested that an atom could form as many ionic bonds as it had “got electrons to cover”. Another student argued that sodium could not form six ionic bonds to surrounding anions unless it became Na^{6+}.

Dichotomous classification of bonding

Students tended to class bonds as either covalent or ionic, even when they had been taught about electronegativity and polar bonding. At the beginning of the A level course students commonly only recognised these two categories, which could clearly be explained in terms of the full shells explanatory principle. Even when the interviews showed that students *could* discuss bond polarity, they spontaneously tended to class polar bonds as covalent (e.g. Al-Cl, B-F, Ca-Cl, C-Cl, C-O, H-F, Si-O, Ag-Cl) or ionic (e.g. Al-Cl, B-F, C-Cl, H-Cl, H-F). Sometimes students suggested that metals also had covalent or ionic bonding.

When students learnt about dative bonds they tended to consider these as "a type of covalent bonding" or "a form of covalent bonding", rather than a polar bond. Although one atom donated both electrons it was considered that "once a dative bond is formed it's the same as a covalent bond".

Bonds and 'just forces'

In the research it was found that during their course students came to recognise that covalent and ionic bonding did not explain all types of interatomic and intermolecular interactions. However there was a tendency to discount anything that could not be explained in terms of the full shells explanatory principle as just a force, and not a proper bond. In a metal for example there would be a force between the atoms, but not a bond. Similarly in a sodium chloride lattice each ion was *bonded* to one counter ion, and *attracted* to five others just by forces. In some cases this was described as "just a weak attraction". One student wrote in an assessment that the bonds in NaCl molecules were ionic but there were "weak" van der Waals' forces "from molecule to molecule".

Indeed intermolecular bonding such as van der Waals' force was not generally considered as true bonding: "not actually a chemical bonding" but "just a type of force". Similarly, solvation was considered to be "*like* a bond" but "just an attraction really". Even in the case of hydrogen *bonding* (where the name might be expected to be somewhat suggestive) students thought that adjacent molecules "don't actually bond" and the hydrogen bond would be "a lot weaker" than "the *proper* bond".

Discussion

The findings presented above make up a set of alternative conceptions initially elicited during interviews with individual colearners, and subsequently found to be represented in other data collected from A level chemistry students. In addition, colearners' statements have been used to prepare survey instruments which have demonstrated that some of these conceptions are widely held (Taber 1997a, 1997c).

It is not claimed that a significant proportion of A level chemistry students would agree with *all* of the propositions given as part of the framework. The octet rule framework *as a whole*, then, may not be a *precise* reflection of the thinking of most individual chemistry students. However, it is more than just a collection of alternative conceptions. It *is* an *alternative conceptual framework* in the sense that its constituent propositions may be shown to be logically connected in learners' explanations. The tendency to class all bonds as *either* covalent *or* ionic relates to the way these types of bonds may be understood in terms of the full shells explanatory principle - while the tendency to class other types of interactions as 'just forces' may likewise be understood to be because these interactions can *not* be easily related to this principle. The notion of ionic molecules follows from only seeing small discrete groups of ions as bonded, which in turn follows from considering the ionic bond as electron transfer, and therefore limiting the number of bonds to the number of electrons that 'need' to be lost or gained by an atom (according to the full shells explanatory principle). The belief that this bond is more than just the forces between ions is related to seeing the transferred electron as retaining a special link with its donor atom, and this is surely influenced by considering the atom as a unit with a unique ontological status. The anthropomorphic nature of the framework treats the atoms as sentient actors trying to satisfy their needs, and reinforces notions such as electrons *belonging* to particular atoms, and bonding being forged by inter-personal acts such as sharing, or donating and accepting, electrons.

The octet rule framework is a model which has pedagogic value. This is because it can be used to explain how some common alternative conceptions may be epistemologically related:they derive from the primacy of the full shells explanatory principle in student thinking. The teacher who can learn to interpret chemistry from this viewpoint will understand why the student

- sees bond type as a dichotomy;
- believes in ionic molecules;
- expects bond fission to always be homolytic;

- considers ‘proper bonds’ and ‘just forces’ to be ontologically distinct rather than just different in magnitude;
- limits the number of possible successive ionisations to the number of valence shell electrons;

and so forth. This teacher will therefore be in a better position to find appropriate demonstrations and counter-examples to challenge the adequacy of such thinking.

Conclusion

The octet rule framework is presented as a model of one common way that pre-university chemistry students think about aspects of chemistry. It would not satisfy Kuiper’s notion of a common alternative framework, as it is unlikely one could find many students whose ideas match all aspects of it precisely. Rather, it is an alternative conceptual framework in the tradition of Gilbert and Watts: it is a composite picture based upon ideas shared by a number of learners; a thematic interpretation of data; a stylised, mild caricature of the responses made by students. Providing it is understood as such, it is a useful pedagogic model of a common strand of alternative thinking that teachers may expect to find amongst their students.

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