

# A Common Core to Chemical Conceptions: Learners' Conceptions of Chemical Stability, Change and Bonding

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## Introduction

This chapter discusses learners' thinking about chemistry at the submicroscopic level, that is, when they think about molecules, ions and atoms, and how they interact. Scientists, and in particular chemists, have extensive explanatory schemes relating to aspects of the structure and properties of materials, based upon the theoretical properties and behaviour of conjectured submicroscopic particles. Indeed, in learning chemistry beyond the most introductory level, talk of molecules, ions, electrons and so forth is ubiquitous, and there is a sense in which no one can be considered to understand chemistry as a modern science unless they appreciate at least some of this conceptual framework for the subject.

It is widely accepted that learners develop alternative understandings of scientific topics, and a major strand of science education research for some decades has explored the nature and consequences of learners' thinking for learning of the science presented in the curriculum (Duit 2009). This work has largely been carried out from a constructivist perspective (Gilbert 1995; Glasersfeld 1989; Sjøberg 2010), where it is acknowledged that learning is largely an iterative and contingent process: what we (think we) know today is a major factor in what we can learn tomorrow. The outcomes of this body of research have variously been described in such terms as misconceptions, alternative conceptions, intuitive theories and a range of other descriptors (Gilbert and Watts 1983; Hammer 1996; Pope and Denicolo 1986). Some of this variation in terminology simply reflects researchers' preferences, and some reflects very real differences in the reported status and nature of the ideas (Taber 2009b).

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In 1998, the present author published a research report deriving from a doctoral study on ‘Understanding Chemical Bonding’, claiming that learners’ ideas in this area appeared to make up an ‘alternative conceptual framework’, that is a largely coherent theory-like basis for thinking about aspects of chemistry (Taber 1998, 1999a). Although my focal topic was chemical bonding, it was clear that this framework was used to think about related themes such as chemical reactions, chemical stability and ionisation energies. The original research was an in-depth interview-based study with a modest number of ‘advanced level’ students (typically 16–19-year-olds) studying chemistry in a further education college in England. However, following up on the original findings, data has since been collected from more diverse samples of students, including some in different educational contexts, and this has offered evidence suggesting that the original findings were generalisable beyond both the original institution and also the English educational system. This is important, as it suggests that the nature of the thinking uncovered in the original research was not largely due to a particular teaching approach, or a particular curriculum specification, but seems to reflect something more basic about the interaction between learners’ minds and the nature of the models presented in chemistry education.

In this chapter, I will:

- Set out the common alternative conceptual framework and explain how it was derived from the original interview study.
- Explain how this ‘octet’ framework is influential across a range of topics in chemistry and, therefore, supports the development of a spread of ‘misconceptions’.
- Review some of the research suggesting this is a common conceptual framework, used by many students in different educational contexts.
- Briefly review the ways in which learners are believed to develop ‘alternative conceptions’ and suggest two likely sources of this common way of thinking about chemistry:
  - Firstly, that this particular idea is a pedagogic learning impediment – that is, that part of the popularity of this alternative conceptual framework derives from the way chemistry is taught
  - Secondly, that, in part at least, the insidious nature of this way of thinking about chemistry reflects intuitive elements of cognition involved in preconscious thought
- Finally, I will suggest what this research indicates about (a) teaching the submicroscopic concepts of science and (b) potentially fruitful areas for further research.

The structure of the early sections of the chapter is ‘pedagogical’, rather than chronological, because it is believed this offers a better narrative for readers. The section entitled ‘[A common alternative explanatory principle adopted by learners to make sense of chemistry](#)’ introduces the key findings from an interview study undertaken with 16–19-year-old college students studying chemistry, concerning how they made sense of the chemical bonding concept (largely based on their prior school learning). In the English context, schooling is compulsory till age 16, and up

to this point, students follow a range of subjects. Students who wish to apply for university courses usually then study for two further years at 'Advanced Level', or A Level, selecting a smaller number of subjects. Most of the students in the original interview study were taking A Level Chemistry, alongside two other subjects that were chosen individually.

The following section, '[An alternative framework for thinking about chemical stability, change and bonding](#)', is based upon the same study but considers how the key ideas were applied and extended in a range of topics that students met during their college chemistry course. Then, the section entitled '[Generalisability of the octet alternative conceptual framework](#)' explores other research that suggests that key aspects of the findings deriving from the original study apply to students learning chemistry in a range of contexts (and are not limited, e.g. to English college students). This section includes discussion both of studies carried out by the present author and his colleagues and of completely independent research that has reported similar findings. Some work that clearly predates the present author's studies is included in this section (rather than earlier) to provide a more coherent review.

Given the space limitations of the chapter, only outline details will be given of the contents of studies mentioned here. Readers are referred to the original published studies for details of samples, methodologies used and precise findings. The purpose here is simply to make the case that findings from a range of studies are providing an increasing evidence base for believing that there is a common way of thinking about chemistry that is acquired by students across different educational contexts.

Research reports giving accounts of the thinking of others are necessarily reporting inferences drawing on data that has been interpreted during analysis. Thinking, ideas, conceptions and other mental phenomena are only indirectly available to others through the way we represent our subjective experience (e.g. through speech, gesture, drawings), and must then be interpreted through the cognitive processes of those others for them to make sense of the representations. To aid readability, I have not always made these provisos explicit, but all references to the ideas, thinking, etc. of my informants need to be understood as my reporting my interpretations of the data collected.

## **A Common Alternative Explanatory Principle Adopted by Learners to Make Sense of Chemistry**

The claim made in the 1998 paper was that among the students interviewed for the study, there was an adoption of a common explanatory principle, that chemical processes can be explained at the submicroscopic level in terms of atoms acting to acquire particular electronic configurations. An immediate complication is that students did not all use precisely the same terms but could refer to atoms *filling their shells* or obtaining *octets* of outer electrons, or acquiring *noble gas electronic configurations*. The common feature was that students recognised that

certain electronic arrangements had an inherent stability (a reasonable interpretation of teaching), and saw the ability to acquire these arrangements as a sufficient basis for explaining chemical processes (which, as will be explained, forms an inappropriate generalisation).

Some of my informants were very generous with their time, allowing me to explore their ideas in a range of contexts, and as their thinking developed during their Advanced Level Chemistry course. For example, one student (given the assumed name Tajinder) was interviewed over 20 times, often for well over an hour at a time, and provided the basis for a particularly detailed case study (Taber and Watts 1997). From this extensive database, it was possible to report on how Tajinder had demonstrated ‘manifold conceptions’, in having several alternative ways of thinking about chemical processes. So during his course, Tajinder drew upon three distinct ways of explaining chemical bonding, and these appeared to make up a repertoire of explanatory principles that could be used as the basis of complementary explanations (Taber 2000b). At the start of his course, one particular type of explanation dominated, which I labelled the ‘*full-shells explanatory principle*’, i.e. that bonds formed to allow atoms to obtain full shells. During his course, as he learnt more chemistry, there was a shift and Tajinder increasingly tended to discuss chemistry instead in terms of the electrical interactions between molecules, ions, nuclei, electrons, etc. (Taber 2001). However, even at the end of his course, Tajinder continued to use the full-shells explanatory principle, if not as frequently as when he began his A level course. Indeed, when he was reinterviewed some years later, his thinking demonstrated a reversion, so that explanations in terms of the needs of atoms to fill their shells once again dominated his answers (Taber 2003a).

In effect, Tajinder had entered the course with a commitment to a key idea he had acquired during school study; during the course, he had shifted away from this idea to some extent, towards the more physical explanations (i.e. explanations based upon physical principles such as the attraction between opposite charges) given in his course, but the original conception was tenacious and was the one he readily remembered some years after completing his course.

Although each student interviewed had somewhat idiosyncratic thinking, all drew to some extent, and usually as a major theme in their thinking, on a version of the full-shells explanatory principle. In general terms, progression in learning for these students was in large part about moving beyond this particular way of thinking, to adopt more scientifically acceptable ideas relating to electrical forces, energy minima and orbital interactions (Taber 1999b).

That is, *students entering the college chemistry course predominantly explained chemical bonding as being how atoms managed to fill their shells (or obtain octets of electrons or noble gas electronic configurations)*. Although students might use different terminology, they would generally see the same species as stable: so generally (besides period 1, hydrogen and helium), references to full shells meant atoms with an octet of outer electrons, even in period 3 and beyond where technically such shells are far from ‘full’. For the sake of a readable account, in this chapter I will ignore individual differences in how students described the desired electron

Covalent bonding	Ionic bonding
Forms between non-metallic elements	Forms between metallic and non-metallic elements
Due to sharing of electrons between atoms...	Due to transfer of electrons between atoms...
...so that atoms have full shells of electrons	...to give ions with full shells of electrons

**Fig. 1** A bonding dichotomy: student conceptualisation of the nature and purposes of chemical bonding

configurations, as generally ‘full shells’ and ‘octets’ and ‘noble gas structures’ may be understood as synonymous in the context of learners’ adoption of a ‘full-shells explanatory principle’ as the main driver for chemical processes.

So for these students, covalent bonds formed so that atoms could share electrons *to give them full shells*, and the ionic bond was the transfer of an electron from a metal atom to a non-metal atom, *to form ions with full outer shells*. Typical understanding may be summarised above (Fig. 1).

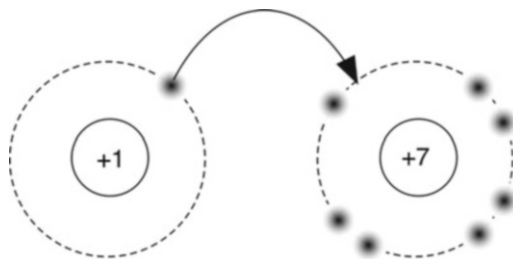
This outlines the typical understanding students brought from their school studies, and which formed the starting point for understanding presentations of chemistry at the submicroscopic level that they met in their advanced (post-school) studies.

### *Covalent Bonding as Electron Sharing*

The notion that covalent bonding is the ‘sharing’ of electrons is not necessarily an alternative conception: chemists themselves often talk in this way. ‘Sharing’ is in effect a metaphor, but among chemists has become a ‘dead’ metaphor (Lakoff and Johnson 1999): one that through familiarity and convention has become adopted as an accepted label. For chemists, the notion of sharing *stands for* how an electron pair can bind two atomic cores through the electrical interactions between positive and negative electrical charges or implies that the shared electrons are understood to be placed in a bonding molecular orbital conceptualised as being formed by the overlap of atomic orbitals.

However, for students in the early stages of this study, sharing electrons formed a bond as it allowed the shared electrons to be counted in the valence shells of both of the sharing atoms and so allowed these atoms to be said to have full shells. That was considered both the reason for the bond forming and for why it acted as a bond. The students held an alternative conception that *the covalent bond formed and held atoms together in molecules because sharing of electrons allowed them to fill their shells*. Students commonly considered electron sharing as a sufficient explanation of bonding and so did not think in terms of electrical interactions.

**Fig. 2** Students commonly identify a chemically unlikely electron transfer between isolated atoms as being the ionic bond



### *Anthropomorphic Nature of Chemical Bonding*

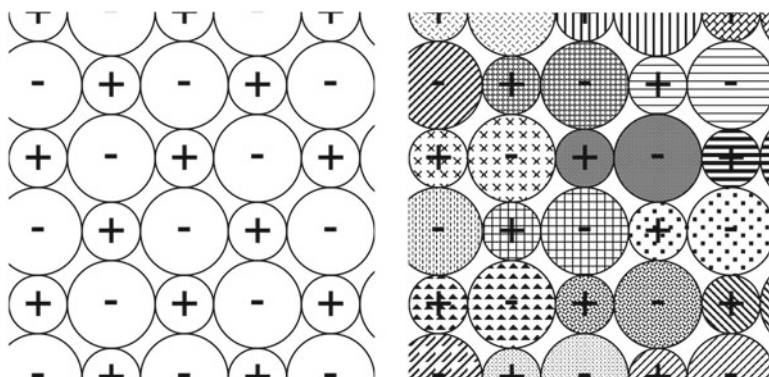
As students generally did not consider the physical forces acting when bonds formed nor conceptualise the bond in terms of an energy minimum – an equilibrium arrangement where attractive and repulsive forces balanced – their explanations of chemical bonding were anthropomorphic in nature (Taber 1998). They referred to atoms *wanting* or *needing* to fill their shells and forming bonds so that they could do so. In other words, in the absence of considering any physical mechanism (such as the force of attraction between a nucleus on one atom and an electron on a different atom), students talked as if atoms were sentient actors in the world. The way students described this was as if atoms *were aware* that they did not have full shells, *desired* full shells, and *actively* did something about it!

My interviewees were students in post-compulsory education and had achieved good grades in their school examinations, and I was rather surprised to find students apparently using anthropomorphic explanations of atomic behaviour without any apparent sense that this was only a metaphorical description. This was a feature I followed up in some interviews. I found some students seemed happy to talk extensively of the feelings and experiences of atoms without any sense of this being inappropriate or suboptimal as part of a scientific explanation. Other students seemed to acknowledge this *must be* a metaphoric form of description, but without this necessarily suggesting to them that it may be an inadequate one (Taber and Watts 1996/2005).

### *An Alternative Conceptual Framework for Ionic Bonding*

When asked about ionic bonding, it was found that, for most students, the most salient idea was that of an electron transfer between atoms (Taber 1994, 1997, 1998). Indeed, for most students, this hypothetical electron transfer event was seen as the ionic bond (see Fig. 2).

This conceptualisation of the ionic bond tended to result in a way of thinking about ionic structures at odds with the models of science. This was described in



**Fig. 3** When shown an image of an ionic lattice (*left-hand image*), some students will happily nominate pairs of ions as being bonded together but only attracted to other equally close counter-ions by weaker forces – conceptualising the structure as containing discrete molecule-like entities (*right-hand image*)

terms of an alternative ‘molecular’ framework for ionic bonding (Taber 1994), with four common features:

- The presence of molecules or molecule-like entities: that ion-pairs (or other units in more complex cases) formed by electron transfer exist as identifiable structural units in ionic lattices.
- The history conjecture: that an ionic bond only exists between ions that have experienced an electron transfer event together.
- The valency conjecture: that an atom can only form as many ionic bonds as the number of electrons it is able to donate or accept in forming an ion with a full outer shell.
- The ‘just forces’ conjecture: that there are two types of interaction in the ionic lattice, ionic bonds (where electron transfer has occurred) and just forces between adjacent ions that are not bonded through having experienced electron transfer.

These ideas form a coherent conceptual framework:

1. Defining the ionic bond as an electron transfer event leads to the history conjecture.
2. The history conjecture implies the valency conjecture.
3. This implies the presence of discrete molecular units such as ion-pairs within the lattice.
4. Which requires the ‘just forces’ conjecture to explain why the molecular units form a lattice.

When shown an image of a slice in an ionic lattice, showing a symmetrical arrangement of ions (similar to that shown in Fig. 3), some students were very happy to nominate which ions were bonded together through having been involved in electron transfer and so to assign ions to discrete units within the structure.



So, in effect, for many students, the ionic solid is conceptualised much like a molecular solid such as sulphur or dry ice, with strong bonds within the molecular units and weaker intermolecular forces holding these units together. Such a model of ionic solids is unhelpful, as it does not explain the strength of the lattice or the solubility of salts (as students tend to think that ion-pairs are the solvated species).

### ***Student Thinking About Metallic Bonding***

In the English interview study, it was found that students generally had strong commonalities in their thinking about both covalent and ionic bonds, tending to think of bonding primarily in terms of the bonding dichotomy presented above (Fig. 1). When students were asked about metallic bonding, they tended to demonstrate more variety in their thinking, with their ideas described as one of the following alternatives (Taber 2003b):

- There is no bonding in metals.
- There is some form of bonding in metals, but not proper bonding.
- Metals have covalent and/or ionic bonding.
- Metals have metallic bonding, which is a sea of electrons.

Some students were aware of the ‘sea of electrons’ model of metallic structure; yet, again, student thinking did not tend to be primarily in terms of electrical interactions, and the metaphoric nature of the ‘sea’ was not always appreciated. Some students drew metallic structures with vast excesses of electrons, reflecting the notion of metallic atomic cores as islands in the electron sea, but ignoring the need for electrical neutrality.

Some students who could not see how metal atoms could have full outer shells in a metal (their key criterion for a chemical bond) did not think metals had any kind of bonding, or at least not full chemical bonds. Others, however, considered the bonding to be ionic (with electrons donated to the lattice, allowing the metal cations stripped of valence electrons to have full shells) or in some way at least *like* ionic or covalent bonding. Some students were prepared to consider that the bond was a dynamic process, so that as the sea of electrons moved around, metal cores could be considered to have full shells at least part of the time. These various schemes allowed the students to make sense of why solid metals might have been formed by atoms that were trying to obtain full electron shells.

### **An Alternative Framework for Thinking About Chemical Stability, Change and Bonding**

In the interview study, each student’s ideas were explored in depth, and each demonstrated variations in the examples they used and how they explained different types of chemical structure. However, there was enough commonality to



propose that there was a common conceptual framework of ideas that was widely adopted by students. The conceptual framework, the octet framework, is not then meant as a set pattern that students demonstrate in all its details, but a model of the common features of students' thinking, many of which were found across most of those interviewed (Gilbert and Watts 1983). This degree of commonality is perhaps not surprising given that there is a logical coherence to many of these ideas. That is, if one starts from the propositions that atoms (1) need to obtain full shells and (2) will act accordingly, then a particular way of making sense of the molecular world follows.

### ***Extending Notions of Bonding***

At the start of their course, the interviewees all knew about ionic and covalent bonding, and perhaps something about metallic bonding, but did not extend the concept of chemical bonding beyond that. During their college course, students learnt about bond polarity, dative bonding, hydrogen bonding, bonds in transition metal complexes, solvation/hydration, and induced-dipole–permanent dipole and induced-dipole–induced-dipole interactions. Much of this challenged their existing conceptions about the nature of chemical bonding and can be considered to be at least partially responsible for shifts in their thinking (Taber 2001).

### ***Polar Bonding***

In college level chemistry, students are taught that covalent and ionic bonds are in effect models of ideal cases, and that in most compounds, bonding is best understood as intermediate between covalent and ionic bonding. The metallic or non-metallic nature of elements is not taught as a dichotomy but in terms of the electronegativity scale, and it follows that ionic-covalent represents a continuum, with bonds found at different points along the dimension. However, for students who already understand bonding in terms of the ionic-covalent dichotomy, the conceptual change needed to see bonding instead in terms of a continuum proves to be a difficult shift – perhaps in part because it requires adopting a rather different *type* of ontology of bonding (Taber 2008b), when research suggests that adjusting aspects of personal ontologies may be something many students find problematic (Chi 1992).

In the interview study, it was found that students were open to accepting a category of polar bond but saw this as a distortion of and/or subtype of covalent bond (see Fig. 4). In part, the tendency to see polar bonds as distorted covalent bonds reflects the full-shells explanatory principle as the common starting point for thinking about bonding. When thinking in terms of an electrical model (as presented in the college curriculum), the bond can be considered as an electron pair

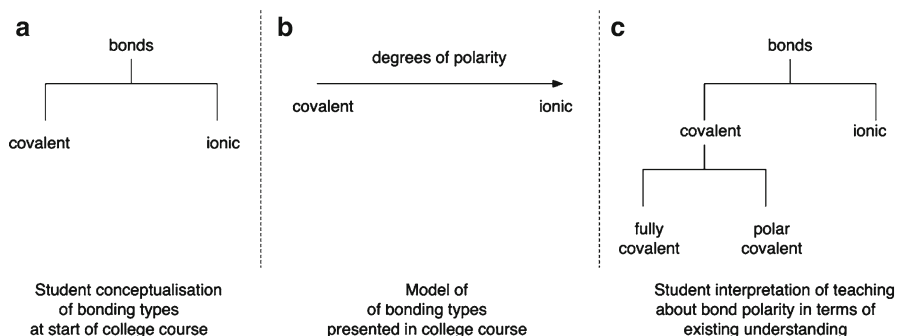


Fig. 4 Student conceptual change on learning about bond polarity

found between two atomic cores, and which may be completely at one side (ionic), evenly shared (covalent) or, more often, somewhere in between (polar). However, the notion of polar bonding does not readily follow from the full-shells explanatory principle, so – for students who consider an atom’s needs to fill its shells as the driving force for chemical processes – teaching about bond polarity is *interpreted* as a secondary electrical perturbation, superimposed on the basic template of a covalent bond. This is not an explicit decision (Pozo and Gómez-Crespo 2005), but simply how teaching is interpreted in terms of the existing conceptual framework: given the starting point (i.e. Fig. 4a, understood as how atoms achieve full shells), learners interpret new teaching to form a hybrid mental model (Gilbert et al. 1982).

### *Intermolecular Bonding*

Although the strongest bonds in chemistry tend to be those related to the ionic, covalent and metallic models, there are other interactions that are also very important. These include the interactions that allow solvation to occur, so that, for example, NaCl, with strong ionic bonds, is readily dissolved in the polar solvent water. Similarly, sulphur, wax and iodine are solids at temperatures where at least one substance with metallic bonding (mercury) is a fluid. The molecules in sulphur, wax and iodine are held together by van der Waals forces, that is, forces due to transient fluctuating dipoles in neutral molecules.

Students who have developed a way of thinking akin to the octet framework tend to think that chemical bonds are formed to allow atoms to achieve full shells, and so various types of dipole–dipole forces (whether due to permanent or transient dipoles) are therefore not considered to be types of chemical bonds. Whilst to some extent professional chemists also tend to distinguish strong chemical bonds from these weaker interactions, they recognise that (a) these different types of interactions can have overlapping ranges of ‘strength’, (b) intermolecular bonding can be highly significant, and (c) chemical phenomena are complex, and often several

types of interactions can be considered to be operating simultaneously. In contrast, students tend to make a sharp distinction between (1) what they see as proper chemical bonds that can be explained in terms of the full-shells explanatory principle and (2) other effects which are 'just forces'.

### ***Hydrogen Bonding***

Hydrogen bonding is a particular case in point, as hydrogen bonding features as an important type of interaction in advanced chemistry courses – for example, explaining the high melting/boiling temperature of water (as well as several other important hydrides), and its low density as a solid, and having a significant role in the structure of proteins and nucleic acids. Indeed, students interviewed in the English study had often met hydrogen bonds in their biology lessons before they were taught about this type of bonding in chemistry classes.

Hydrogen bonds cannot be explained in terms of the full-shells explanatory principle, as the atoms involved are already formally bonded, and so from such a perspective, there is no reason why an oxygen atom, for example, which already has a full shell, would share a nonbonding electron pair with a hydrogen atom, which also already has a full shell of electrons. In the English study, it was found that when some students came across 'hydrogen bonds' in their biology lessons, they simply assumed this was a reference to covalent bond involving hydrogen and so misconstrued what the hydrogen bond was in the structures being discussed (Taber 1998). The label 'bond', and the significant role in holding structures together, was construed in terms of their existing notion of what counts as a bond.

### ***Implications of the Ownership of Electrons***

The anthropomorphic way of thinking and talking about atoms led some students to consider electrons to permanently belong to specific atoms (Taber 1998). This certainly played a part in thinking about ionic structures in molecular terms: two ions were considered bonded by their history, as the anion included an electron that actually belonged to the cation. Indeed, this was sometimes understood as a temporary arrangement, so it was suggested that in a double decomposition (precipitation) reaction, there would be a phase where a previous electron transfer was reversed, so that a new electron transfer could take place to form new ionic bonds (Taber 2002b).

Some students did not feel that the electrons in a covalent bond would be equally attracted to both nuclei, as (they argued) a nucleus would exert more force on *its own* electron. On bond fission, it was then expected that each electron would return to its own atom. The influence of this way of thinking appeared to even be retained on learning about orbital models of atoms and molecules, so that a student considered that the atoms retained their own hybridised atomic orbitals in the

molecule despite knowing that those atomic orbitals are considered to have been recombined into molecular orbitals (Taber 2005).

### ***Stability of Chemical Species***

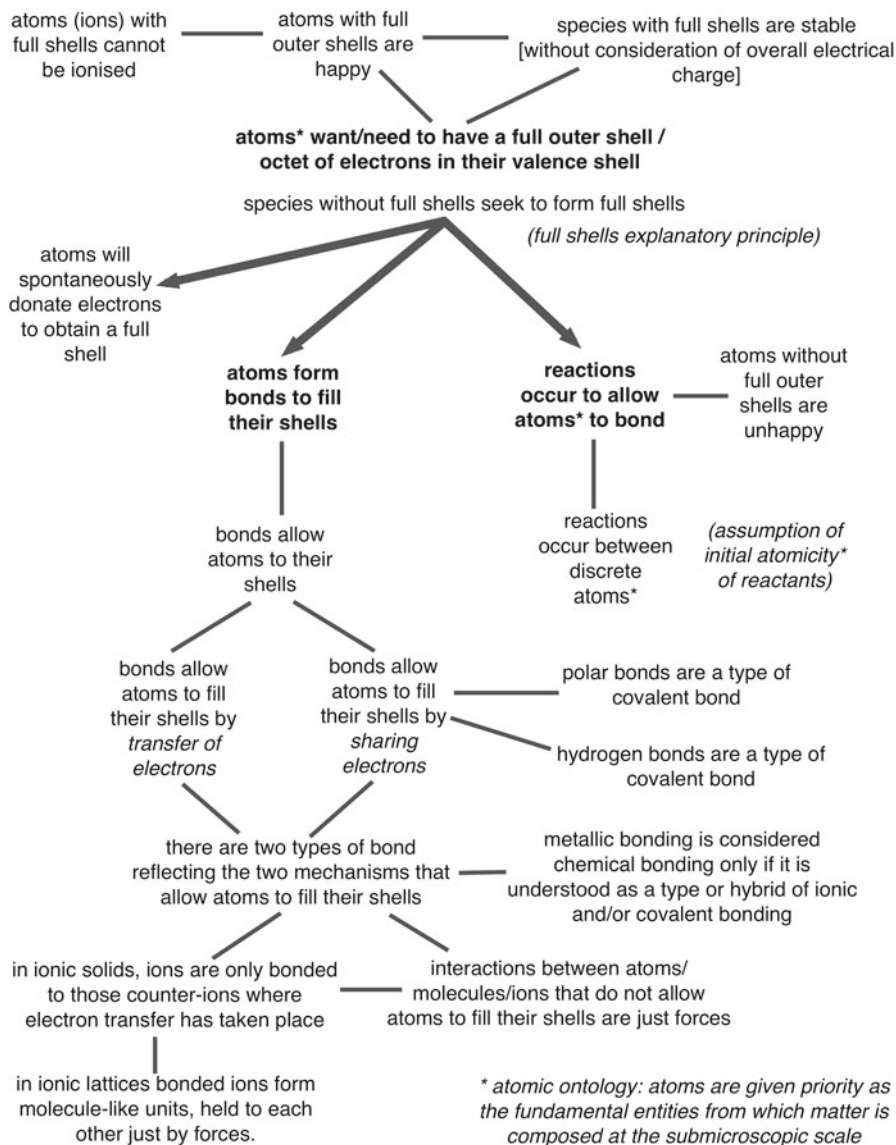
The full-shells explanatory principle is based around the stability of certain electronic configurations. This reflects the ‘octet’ rule, which is a useful heuristic for predicting stable molecules and ions. However, students commonly find the idea that full shells are stable to be especially attractive and so overgeneralise the rule. So students would commonly consider a neutral sodium atom to be less stable than a  $\text{Na}^+$  cation because the latter has a full outer shell of electrons, an octet structure. Such a judgement is unhelpful in the absence of a chemical context. It was found that most students thought that once an electron was removed from a sodium atom, it would not be able to return, because the ion had a stable electronic configuration. Indeed, the students commonly thought that a sodium-seven-minus ion ( $\text{Na}^{7-}$ ) with an electronic configuration of 2.8.8 would be more stable than a sodium atom (Taber 1998).

### ***Perceptions of Chemical Reactions***

A final area where ‘octet thinking’ seems significant is how students think about chemical reactions and *what changes in chemical change*. Not only do students commonly think that bonds form to allow atoms to obtain full shells, but many also suggest that this is the driving force for chemical reactions (Taber 1998). So for many students, chemical reactions occur to allow atoms to fill their shells. Of course, this means making *an assumption of initial atomicity* – such as in thinking about the formation of ionic compounds, where it is assumed the reactants are composed of isolated metal and non-metal atoms. The commitment to an assumption of initial atomicity can be sufficient to lead to students ignoring available information that should make it clear that, in most reactions, the reactants as well as the products comprise of species that already have stable electrical configurations.

## **Generalisability of the Octet Alternative Conceptual Framework**

The octet framework (see Fig. 5) was initially developed as a model to describe common aspects of student thinking deriving from an interview-based study that probed into the understanding of chemical bonding and related topics, working with student volunteers studying chemistry in a single further education college in England (Taber 1998). These students showed common ways of thinking about



**Fig. 5** The octet framework – an alternative conceptual framework comprising a network of ideas built around a core alternative conception

chemistry from early in their college course. As the college took students from a range of schools in the local area, and the interview sample had not been taught school chemistry by the same teachers, it seemed unlikely the common features of student thinking could be put down to an idiosyncratic teaching approach. Yet, it is

clearly a major jump to assume that findings from students in one institution can be unproblematically generalised nationally or perhaps even globally.

However, there is strong evidence to suggest that at least some aspects of the octet framework are common features of student thinking in various institutional and national contexts. This evidence consists of:

- (a) How aspects of the findings of the English interview study reflected findings reported by other researchers in other educational contexts.
- (b) More recent studies in various national contexts have reported findings which seem to reflect aspects of the octet frameworks.
- (c) Probes set up to test-out some specific aspects of the findings in the English study (Taber 2000a) have suggested that some aspects of thinking that are part of the octet framework are well represented among other student groups, both in the UK and beyond.

The latter strand of evidence was in particular supported by the Royal Society of Chemistry's 'Challenging Chemical Misconceptions' project (Taber 2002b) to provide classroom tools for teachers to diagnose student misconceptions (Taber 2002a). This provided the opportunity to enrol classroom teachers who would use diagnostic probes (some especially written for the RSC project) with their own classes. In this way, it was possible to test out the popularity of ideas elicited in the original interview study in a range of schools and colleges in different parts of the UK.

Some of these probes have since been used to survey groups of students studying chemistry in other countries, or in the case of one of the probes, as the starting point for developing a new instrument that was then applied in various national contexts. Space here does not allow an extensive review of all relevant studies but hopefully will allow the presentation of sufficient evidence to make the case that the octet framework seems to reflect aspects of student thinking about chemistry at the submicroscopic level across curriculum, national, and language contexts.

### *Anthropomorphism and Atoms*

The octet framework is based around explaining chemical processes in terms of the needs (wants, desires) of atoms. Whilst chemists, and teachers, may use this kind of language, they are aware it 'stands for' underlying physical processes (e.g. electrical interactions). In the English study (Taber 1998), it was found that the 16–19-year-old students spoke as though the needs of atoms could be a sufficient basis for explaining chemical processes.

This reflects the earlier findings of Griffiths and Preston (1992) who had interviewed students of the same age in Canada and who reported that over half of their sample thought that atoms were 'alive'. In a study with US undergraduates studying chemistry, Nicoll (2001, p. 715) reported that 'it was noted throughout the course of

the interviews and analysis that students ascribed sentience to atoms and molecules. Students continually referred to atoms “wanting” electrons; to “happy”, stable molecules; and to atoms “seeking out” electrons’. She noted that ‘it was difficult to determine whether students in this study actually did believe that the atoms and molecules were animate, or whether they were simply using the analogies that their teachers had given them’ (p. 715). Nicoll offered the example of:

Melissa, a freshman in general chemistry for science and engineering majors, stated, for example, ‘... you have your noble gases that have that full octet: they’re happy’. ... she did not give any further explanation of all the orbitals being full, stability, or paired electrons. Rather, her complete explanation was that they were ‘happy’. (p. 715)

In a more recent study undertaken with Turkish year 11 students, Ünal and colleagues (2010) reported students explaining chemical bonding in terms of the ‘needs’ of atoms to full their shells. Research undertaken with Swedish high school students has also found them using anthropomorphic accounts of atoms wanting or needing to obtain full electron shells (see the contribution by Taber and Adbo in chapter ‘[Developing Chemical Understanding in the Explanatory Vacuum: Swedish High School Students’ Use of an Anthropomorphic Conceptual Framework to Make Sense of Chemical Phenomena](#)’, this volume).

### *Covalent Bonding as Electron Sharing*

Chemists commonly use the metaphor of a covalent bond being a shared pair of electrons, but in the English interview study (Taber 1998), the 16–19-year-old students commonly thought that this was a sufficient definition of a covalent bond (as sharing electrons allowed atoms to obtain full shells). This was reflected in a case study of an Australian grade 11 student, where Harrison and Treagust (2000) report the student telling them that ‘the atoms in a covalent bond share electrons so that each atom has a full outer shell’ (p. 369).

Coll and Treagust (2001) report an interview study with Australian students at different levels and reported that ‘learners view covalent bonding as the sharing of electrons, with the secondary school and undergraduate learners relating this specifically to the octet rule of full shell stability’ (p. 369). The two postgraduate students interviewed in this study also referred to covalent bonding in terms of electron sharing, although this was one among several models used. In similar research carried out in Australasia (Aotearoa/New Zealand and Australia), Coll and Taylor (2001) interviewed students at three levels. They reported that the explanations of covalent bonding of secondary students were based on ideas of sharing electrons and the octet rule. Coll and Taylor also found that undergraduate and postgraduate students talked in terms of atoms sharing electrons. They reported an undergraduate chemistry student referring to how in an iodine molecule, the atoms would ‘quite happily share with each other’ (p. 180) and a postgraduate chemistry student talking of how a hydrogen



atom ‘needs two’ electrons ‘to fill its valence shell’ where other atoms ‘need eight’ (p. 181) – although these students also had more scientific models available to think about the chemistry. In their Turkish study, Ünal and colleagues (2010) report year 11 students also talking of the sharing of electrons as a sufficient basis to explain the covalent bond.

### *Ionic Bonding as Electron Transfer*

In the English interview study, it was found that students associated ionic bonding with electron transfer between atoms, leading to molecule-like entities (ion-pairs in the case of NaCl) within the lattice (Taber 1998). This reflected earlier research by Butts and Smith (1987) in Australia, who interviewed year 12 chemistry students and found 10 (out of 26 interviewees) referred to molecules of NaCl. These authors found few of their interviewees had a conventional understanding of the ionic bonding between ions in the lattice.

A diagnostic instrument, developed on the basis of student comments in the English interview study, was administered by class teachers to UK secondary school students (14–16-year-olds) and Advanced Level students (16–19-year-olds). It was found that students commonly agreed with statements based on the ‘molecular’ framework for thinking about ionic bonding, molecules being formed, and ions having ionic bonds only where electron transfer was considered to have occurred, and interacting with other neighbouring counterions just through forces (not chemical bonds). The overall results suggested that many students tended to hold a mixture of ‘molecular’ and target ideas, with some evidence of progression from school to college level study, especially among classes who had been taught the topic at Advanced Level. However, even among these students, some aspects of the alternative framework were popular (Taber 1997).

A version of the diagnostic instrument used in the UK study (Taber 2002a) was translated to produce Greek and Turkish versions. It was found that first-year university students in both these national contexts commonly judged true statements based on the alternative molecular framework for ionic bonding, although the patterns of response did vary between the three national contexts (Taber et al. 2012).

In their Australasian study, Coll and Taylor (2001) reported students appreciating the electrical nature of ionic bonding, although they also reported students associating ionic bonding with electron transfer. They reported one secondary student describing ionic bonding as ‘where they donate electrons and receive electrons’ (p. 179) and a reference to a sodium atom that ‘prefers’ to lose an electron (p. 180). In a study carried out in New Zealand, Coll and Treagust (2003) reported that among secondary level students they interviewed, the octet rule was seen as the sole driving force for the formation of ionic bonding, with electron transfer as its consequence. In a review of student answers on the Israeli matriculation examination taken by 17–18-year-olds, Levy Nahum and colleagues (Levy Nahum et al. 2004) found examples of references to sodium chloride consisting of two ions and comparisons

of the strength of forces between molecules in sodium chloride and potassium iodide. In their study undertaken with Turkish year 11 students, Ünal and colleagues (2010) reported students talking about ionic bonds in terms of electron transfer, and one of the interviewees they quote explicitly referred to how this would form a molecule.

### ***An Octet Criterion of Chemical Bonding: Metallic Bonding***

In the UK interview study, the purpose of chemical bonding was seen by students as allowing atoms to have complete shells of electrons (Taber 1998), so students either did not consider metallic bonding as chemical bonding or tried to explain it in terms of covalent or ionic bonding types that made sense to them in terms of atoms achieving full shells (Taber 2003b).

Coll and Taylor (2001) reported that in their Australasian interview study, some of the secondary students tried to make sense of metallic bonding in terms of the octet rule and the formation of covalent bonds. One of the postgraduate chemistry students they interviewed admitted to not actually thinking of there being bonding in metals. Acar and Tarhan (2008) reported a study undertaken with 9th grade (15-year-old) students in Turkey where an intervention group learning about metallic bonding were found to demonstrate lower levels of common misconceptions after teaching than a control group. Among the control group, students were found to demonstrate high levels of misconceptions that

- The bonding in metals was ionic bonding, or the bonding in metals was like ionic bonding.
- The bonding in metals was covalent bonding.
- There were weak forces (rather than chemical bonding) holding a metal together.

These various alternative conceptions were found at levels in a range from about a quarter to over three-fifths of the control group (but at much lower levels in the intervention group).

### ***An Octet Criterion of Chemical Bonding: Polar Bonding***

In the English interview study, it was found that rather than seeing polar bonding as intermediate between the extreme case of the ionic and covalent models of bonding (a perspective taught in the college chemistry course and sensible when bonding is considered primarily as an electrical interaction), the English students tended to see bonding as in essence either ionic or covalent (understood in terms of the two distinct mechanisms for atoms completing shells), with polar bonding seen as a subcategory of the covalent case.

Prior to the English interview study, Peterson, Treagust and Garnett had reported a study with secondary students in South Australia where it was found that over a fifth of year 12 and a third of year 11 students ‘held misconceptions relating to bond polarity which indicated confusion regarding the unequal sharing and position of the electron pair in many covalent bonds...[and had not] not considered the influence of electronegativity and the resultant unequal sharing of the electron pair on bond polarity’ (Peterson et al. 1986, pp. 44–45). A more recent study using the same methodology among undergraduate students in Brunei found that about a third ‘had the misconception that equal sharing of electron pair occurs in all covalent [sic] bonds’ (Topper 1990, p. 41). In their study undertaken with Turkish year 11 students, Ünal and colleagues (2010) reported some of their interviewees discussing two types of covalent bond, with those formed between two atoms of the same type (i.e. same element) and polar bonds, which was simply the term used for covalent bonds formed between two different non-metal atoms.

### ***An Octet Criterion of Chemical Bonding: Hydrogen Bonding***

Students in the UK interview study tended to limit their category of chemical bonding to those cases where bonding clearly enabled atoms to have full shells. Some students understood hydrogen bonding as a type of chemical bonding but only because they interpreted the hydrogen bond as simply a covalent bond involving hydrogen (Taber 1998). Similarly Henderleiter and colleagues (Henderleiter et al. 2001) reported from a study with US university students that during interviews, some undergraduates ‘confused hydrogen bonding with a covalent bond between hydrogen and some other atom’ (p. 1128).

Levy Nahum and colleagues (Levy Nahum et al. 2004) report an interview with a student who initially appeared to have a sound understanding of hydrogen bonding, but who on probing offered a confused account, and at one point indicated the O–H bond in a diagram of a water molecule as a hydrogen bond. One of the year 11 Turkish students quoted in Ünal and colleagues’ (2010) study explained that there was ‘no difference’ between a covalent and hydrogen bond, except in the latter case one of the atoms bonded was hydrogen, so that the hydrogen bond in HCl was a covalent bond (p. 19).

### ***Inherent Stability of Species with Full Shells***

A key aspect of student thinking in the UK interview study was that species with ‘full’ valence electron shells (usually actually octets of electrons) had an inherent stability (Taber 1998). This finding was followed up through the development of a set of diagnostic probes asking students to compare the stability of related

species (Taber 2002a). When students from a range of institutions completed these probes, they commonly ascribed stability to chemically unlikely species, such as  $\text{Na}^{7-}$ ,  $\text{Be}^{6-}$ ,  $\text{C}^{4+}$ ,  $\text{C}^{4-}$  and  $\text{Cl}^{11-}$ . Something like half of the students surveyed, thought that excited chlorine atoms with an outer-shell octet (i.e. configurations 1.8.8 or 2.7.8) would be more stable than the ground state (2.8.7) atom (Taber 2009a).

This notion that full shells or octets have some inherent stability influences the way students think about ionisation processes. Students demonstrate a number of common alternative conceptions about ionisation energy, suggesting they do not readily appreciate the basic electrical principles scientists use to think about atoms. In particular, some students suggest that ionisation will occur spontaneously to give a species with a full shell (Taber 2009a), and/or that once an ion with a full shell is produced, no further ionisation would be possible. In their Australasian study, Coll and Taylor (2001) reported one postgraduate chemistry student describing how a sodium atom ‘prefers’ to lose an electron (p. 180).

A diagnostic probe was prepared to explore student conceptions of this topic and completed by students in various institutions, demonstrating that alternative conceptions found in the UK interview study were common among students in other schools and colleges (Taber 1999c, 2002b, 2003c). Daniel Tan and colleagues based in Singapore took this instrument as the starting point for developing a two-tier multiple-choice instrument (Treagust 1988) to explore student understanding of the topic of ionisation energy (Tan et al. 2005), a process that involves cycles of interviewing students. It was found that the alternative conceptions identified among UK students were reflected in a large sample of Singapore students taking chemistry at the same (Advanced) Level (Taber and Tan 2007). The same instrument (translated as appropriate) was also used to collect data from students in several other national contexts (Spain, China, New Zealand and the USA), and again it was found that students in these contexts commonly demonstrated alternative conceptions based on the octet framework (Tan et al. 2008). It was also found that graduates preparing to be chemistry teachers in Singapore commonly demonstrated the same ideas (Tan and Taber 2009).

### ***Driving Force for Chemical Reactions***

In the original interview study, English students suggested that chemical reactions took place so that atoms could obtain full electron shells (Taber 1998). A classroom probe was prepared asking students why hydrogen reacted with fluorine (Taber 2002a). Despite the students being given a formulae equation for the reaction (i.e. showing that the reactants were  $\text{H}_2$  and  $\text{F}_2$ ), students commonly ‘explained’ the reaction in terms of the needs of the hydrogen and fluorine *atoms* to fill their shells (Taber 2002b) – even after being taught chemical ideas about why reactions occur (based on thermodynamics, bond enthalpies and the like). Interviews with Swedish high school students have also found students explaining

that reactions occur because atoms look to complete their outer electron shells (see the contribution by Taber and Adbo in chapter ‘[Developing Chemical Understanding in the Explanatory Vacuum: Swedish High School Students’ Use of an Anthropomorphic Conceptual Framework to Make Sense of Chemical Phenomena](#)’, this volume).

## The Origin of the Alternative Conceptual Framework

The octet framework was developed as a model based on an interview study in one context, and it is important to acknowledge that although (as the previous section shows) elements of the framework appear to be demonstrated by students in various national contexts, there has not any research specifically been designed to replicate the findings of the English study as a whole. Despite this, there is a strong case for considering that ideas about atoms striving to fill their shells being the main driver for chemical processes seems to act as a common core to student thinking at upper secondary, college and even university level in a range of educational contexts.

It is possible to suggest several potential origins for the alternative conceptions that students develop (Andersson 1986; Claxton 1993; Gilbert et al. 1982; Hammer 1996; Smith et al. 1993; Solomon 1987; Talanquer 2006), although in reality these different factors are likely to interact (Taber 2009b). One source of such conceptions is the way people intuitively make sense of the physical world in which they live. So, for example, the common conception that a force is needed to maintain movement would seem to be an intuitive idea based on abstraction of experience of moving objects in the physical world (McCloskey 1983). According to diSessa (1993), a good many alternative conceptions that have been found in physics topics would seem to derive from the application of intuitive knowledge elements that seem to reflect the brain’s natural tendency to abstract patterns from experience of the world.

Another source of alternative conceptions is the wealth of cultural ideas that are communicated informally through family, friends, media, etc. (Solomon 1987). The cultural origins of such ideas will be reflected in their incidence in different contexts (Brewer 2008). So notions that getting wet can lead to catching cold, and that sitting under a certain type of tree can lead to getting pregnant, tend to be common in different populations. Other ideas derive from the way individuals interpret linguistic cues or from their own analogical links between what they are told and already know. The expectation that neutralisation necessarily leads to a neutral product may be an example of how a common alternative conception can form in this way (Schmidt 1991). Annie, who interpreted the ‘+’ and ‘-’ symbols used to show ionic charge as indicating deviation from full shells (so that ‘+’ means one electron *more than* a full shell), represents a more idiosyncratic example (Taber 1995).

## ***The Role of Curriculum and Teaching in Encouraging the Octet Framework***

The theoretical world of molecules, ions and electrons is not directly available to learners, so alternative conceptions are unlikely to be formed either by *direct* abstraction from experience or by acquiring folk knowledge (as talk about molecular structure and the like is seldom part of everyday lifeworld discourse). The example of Annie acquiring an *idiosyncratic* understanding of an aspect of chemists' representations of the molecular world should not surprise us: students learn about the unfamiliar by interpreting teaching through their existing repertoire of knowledge and ideas. Another student I worked with spoke of atoms with *electron shields*, having apparently misheard electron shells as an alternative term that made sense to him.

However, the existence of a very common alternative conceptual framework based on the needs and behaviours of atoms does present a problem. At present, there is limited definitive research to explain the origins of the octet framework as a common core to student thinking about chemistry at the submicroscopic level. After having worked on this issue for some years, my hypothesis about this is twofold.

In part, I consider teaching models and approaches partially to blame. Whilst the full-shells explanatory principle is not a valid one, many introductory school chemistry textbooks can be quite easily read as implying that bonds form so that atoms can fill their shells. Unfortunately, school chemistry seldom offers a viable explanation for why chemical reactions occur, so the octet rule seems to be adopted as an explanatory principle to fill the 'explanatory vacuum' (see also my work with Karina Adbo reported in this volume). Schematics representing bond formation often seem to imply that compounds are formed by the reaction of atomised elements (an isolated carbon atom reacts with four nascent hydrogen atoms, not two hydrogen molecules). Figures showing electron transfer (cf. Fig. 2) are presented when discussing the ionic bond, despite such figures having little relevance to the formation of ionic compounds. Teachers may use anthropomorphic language when discussing chemical processes, something research suggests makes many students more receptive to abstract topics (Day et al. 2008). The work of Daniel Tan with his graduate trainee chemistry teachers even suggests that in some cases, teachers themselves hold the alternative conceptions, so are presumably teaching flawed ideas to their classes in good faith (Taber and Tan 2011).

## ***Chemical P-Prims?: The Role of Implicit Knowledge Elements in Developing the Full-Shells Explanatory Principle***

However – even if it transpires that chemistry teachers worldwide are commonly teaching generations of students according to the octet alternative conceptual framework – that cannot be the whole story. Given that the curriculum generally offers

more scientifically accurate models as target knowledge, there must be some reason why qualified chemistry teachers continue to teach in ways that lead to many of their students acquiring alternative conceptions about such core chemical concepts as bonding, stability and chemical change.

This would seem to be that some of these alternative ideas must be intuitively appealing. Although we would not expect students to directly develop intuitions about the world at the scale of molecules and ions (indeed, we know such ideas are counterintuitive for many learners), when students do meet atoms, molecules and the like in school science, their existing implicit knowledge of the world acts as the cognitive resource for making sense of the unfamiliar molecular realm. That is, students already have implicit knowledge elements that although not ‘about’ atoms and molecules, are cued in the context of being taught about the existence of these submicroscopic entities (Brown and Hammer 2008).

This is conjecture, but not pure speculation. Two of the common alternative conceptions about ionisation that seem to have appeal across national contexts would seem to be good candidates here. The notion that ‘full’ shells, with their symmetry, might be especially stable, and the way students understand nuclear force to be shared among valence electrons, seem to both reflect common patterns that can be abstracted from wide experience in the world (Taber and Tan 2007).

The work of diSessa and colleagues has uncovered many potential candidates for such intuitive knowledge elements, labelled as phenomenological primitives or p-prims, that are likely abstracted from common experience of the world and come to be applied to understand (or misunderstand) physical principles (diSessa 1983, 1993; Smith et al. 1993). These p-prims are considered to be domain independent and so should provide conceptual resources for making sense of all topics regardless of disciplinary boundaries. Certainly Andersson (1986) has proposed that a common intuitive knowledge element about the way agents bring about actions when changes occur in the world could act as a common core to learners’ conceptions across science.

To date, there has been limited research to develop this perspective in chemistry education. However, analysis of interviews into students’ explanations of basic physical and chemical changes carried out by Alejandra García Franco has suggested a number of possible candidates for implicit knowledge elements acting in chemistry, some of which may well turn out to link closely with diSessa’s p-prims (Taber and García Franco 2010).

Teaching and learning are complex processes, but Fig. 6 presents a schematic of how scientific ideas become simplified, interpreted and moderated as they are represented in classroom teaching and inform student learning.

### ***Implications for Pedagogy and Directions for Research***

There is scope for a lot more research into this topic. It is clear that students commonly develop alternative ideas about the submicroscopic models so central to chemistry, and that there are some strong commonalities in the alternative



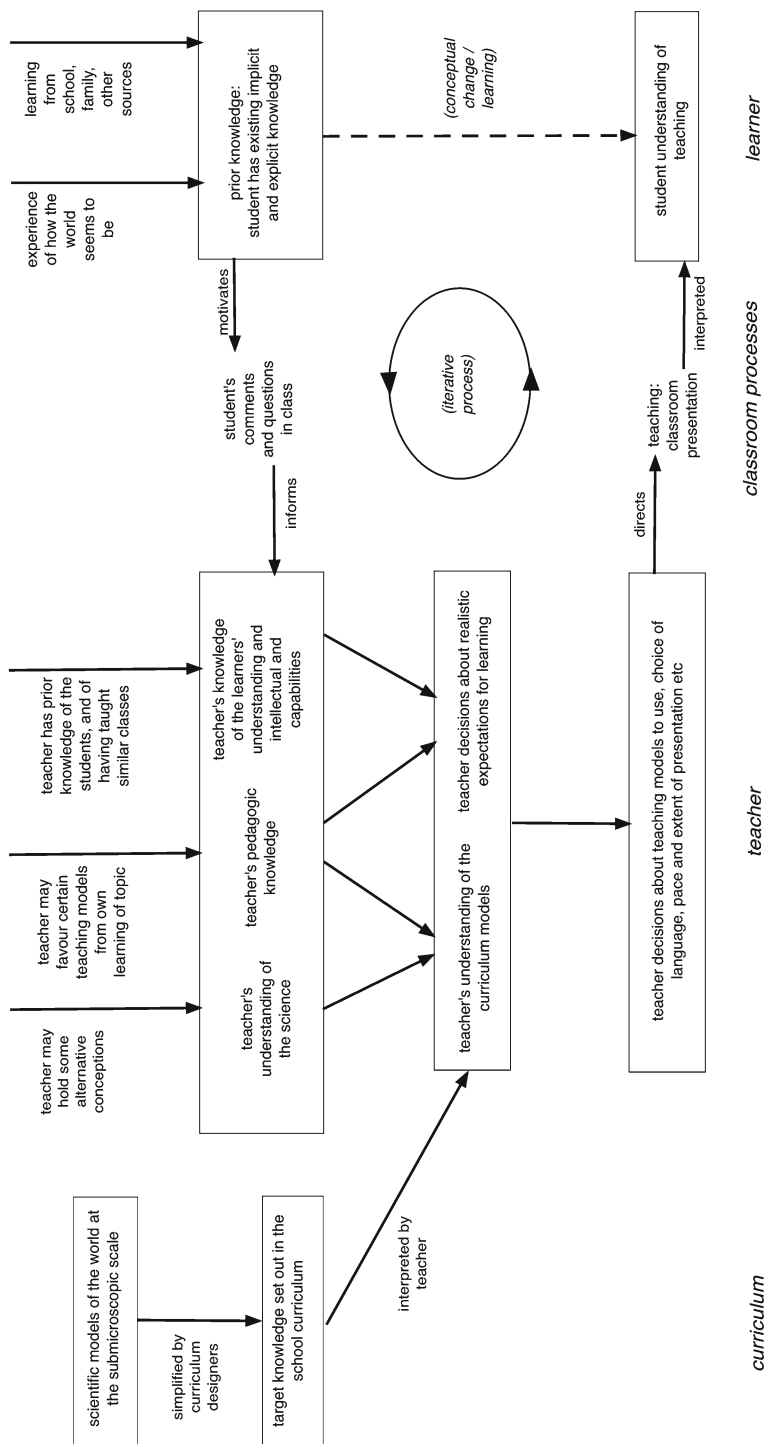


Fig. 6 Scientific ideas are modified both deliberately and inadvertently in classroom teaching

conceptions developed by many learners. It also seems clear that once students acquire something like the full-shells explanatory principle, it readily stands in place of more scientific understanding and impedes progression in learning. There is also a good case that the factors leading to students developing ‘octet framework thinking’ are not limited to a particular curriculum, language or teaching style.

The available evidence should certainly lead to teachers questioning certain common teaching practices: introducing bonding as a dichotomy of two main types, drawing imaginary electron transfer events when teaching ionic bonding, relying on anthropomorphic language to describe bonding and other processes, and overemphasising the octet rule would all seem to readily mislead students. Teaching bonding as primarily a matter of forces, emphasising how reactants (as well as products) tend to obey the octet rule, and stressing that stability is always a relative judgement (e.g. that overall charge is a factor as well as electronic configuration) would seem to be worth stressing more.

It seems that the teaching of chemical bonding is a topic that could be fruitful for researchers interested in teaching and teacher thinking, and – in particular – how knowledge is represented in curriculum and the classroom. Scientific knowledge is represented (i.e. necessarily as something rather different) in the formation of ‘target knowledge’ in the curriculum; and during the processes of classroom teaching, teachers then represent their own interpretations of that target knowledge in the decisions they make about level of treatment, concept sequencing and selection of teaching models (including choices of teaching analogies). Perhaps ‘distortion’ is inevitable in these processes of simplification and re-representation because of concerns about what students are ready to deal with or limitations in teachers’ own subject knowledge or pedagogical content knowledge, for example (see Fig. 6). From the perspective of didactic transposition (Chevallard 2007), it would be expected that ‘knowledge’ would itself change its form in different institutional settings: chemical knowledge in the school science classroom adopts a different niche to chemical knowledge in the research laboratory or the discourse of the professional community. So, for example, anthropomorphic and teleological forms of explanation that may be criticised in the context of the work of the research scientist expected to offer mechanistic explanations may take on a different status among teachers more concerned with supporting student’s attempts at meaning-making. This is perhaps an under-researched theme in science education, and the present topic area might offer a fertile context for enquiries.

There is certainly scope for research to develop our understanding of student thinking:

- To what extent is the octet framework common across different educational contexts?
- Are there variations in the incidence of students developing specific aspects of the framework across contexts that might give clues to how these ideas are acquired and reinforced?
- Can studies of the teaching of these topics in different classrooms relate students’ developing thinking to the teacher’s employment of different models, sequencing, language or emphasis?

The exploration of the importance of implicit knowledge elements has had much less attention in chemistry than in physics, and there is much scope for characterising the particular intuitive knowledge elements that students seem to be using to interpret teaching, with potential perhaps to develop a much more fine-grained constructivist approach to teaching (Taber 2008a): that is, knowledge of the available repertoire of primitive knowledge elements could inform the planning of instruction to take advantage of the way learners tend to implicitly understand the world.

The original interview study that was the first stage of the programme of research discussed here was undertaken with a necessarily modest number of informants questioned in some detail over a period of time, but the generality of some of the findings from that study have been tested out through survey-based techniques, showing how these different approaches are complementary in science education. The use of case studies provided some insight into the course of conceptual change in some individual learners. In particular, whilst the notion of learners having conceptual frameworks in science has been criticised in some quarters (Claxton 1993; Kuiper 1994), this certainly seemed an appropriate characterisation of the organisation of student knowledge in this topic (chemical bonding) in the 16–19-year-old learners investigated (Taber 1998). The nature and mechanisms of conceptual change have continued to be the subject of considerable scholarship and diversity of view (Vosniadou 2008), and it seems very likely that a full account of conceptual change in science learning will be nuanced and somewhat complex. For example, the research reported here found examples both of students adopting hybrid models (Justi and Gilbert 2000) when modifying existing understanding to accommodate somewhat disparate ideas and major (somewhat ‘revolutionary’) shifts (Thagard 1992) in the frameworks adopted in response to the slowly evolving ‘conceptual ecology’ (diSessa 2002) in which the chemical concepts were embedded. However, this work began with students entering college, and there would be much value in beginning a longitudinal study earlier during secondary education and possibly including microgenetic approaches (Opfer and Siegler 2004) to exploring students’ thinking during periods when the topic is being studied in class.

So there is much more work to be done. However, what seems very clear is that the outcome of current chemistry teaching for many students throughout the world seems to be the adoption of the core idea that the main driver for chemical processes is atoms ‘trying’ to fill their shells. That is scientifically dubious and impedes progression in learning the subject and so presents a serious challenge to chemistry educators.

## References

- Acar, B., & Tarhan, L. (2008). Effects of cooperative learning on students’ understanding of metallic bonding. *Research in Science Education*, 38(4), 401–420. doi:10.1007/s11165-007-9054-9.
- Andersson, B. (1986). The experiential gestalt of causation: A common core to pupils’ preconceptions in science. *European Journal of Science Education*, 8(2), 155–171.

- Brewer, W. F. (2008). Naïve theories of observational astronomy: Review, analysis, and theoretical implications. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 155–204). New York: Routledge.
- Brown, D. E., & Hammer, D. (2008). Conceptual change in physics. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 127–154). New York: Routledge.
- Butts, B., & Smith, R. (1987). HSC chemistry students' understanding of the structure and properties of molecular and ionic compounds. *Research in Science Education*, 17, 192–201.
- Chevallard, Y. (2007). Readjusting didactics to a changing epistemology. *European Educational Research Journal*, 6(2), 131–134.
- Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. N. Giere (Ed.), *Cognitive models in science* (Vol. XV, pp. 129–186). Minneapolis: University of Minnesota Press.
- Claxton, G. (1993). Minitheories: A preliminary model for learning science. In P. J. Black & A. M. Lucas (Eds.), *Children's informal ideas in science* (pp. 45–61). London: Routledge.
- Coll, R. K., & Taylor, N. (2001). Alternative conceptions of chemical bonding held by upper secondary and tertiary students. *Research in Science & Technological Education*, 19(2), 171–191.
- Coll, R. K., & Treagust, D. F. (2001). Learners' mental models of chemical bonding. *Research in Science Education*, 31(3), 357–382.
- Coll, R. K., & Treagust, D. F. (2003). Investigation of secondary school, undergraduate, and graduate learners' mental models of ionic bonding. *Journal of Research in Science Teaching*, 40(5), 464–486.
- Day, C., Sammons, P., & Gu, Q. (2008). Combining qualitative and quantitative methodologies in research on teachers' lives, work, and effectiveness: From integration to synergy. *Educational Researcher*, 37(6), 330–342. doi:10.3102/0013189X08324091.
- diSessa, A. A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 15–33). Hillsdale: Lawrence Erlbaum Associates.
- diSessa, A. A. (1993). Towards an epistemology of physics. *Cognition and Instruction*, 10(2&3), 105–225.
- diSessa, A. A. (2002). Why “conceptual ecology” is a good idea. In M. Limón & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29–60). Dordrecht: Kluwer.
- Duit, R. (2009). *Bibliography – Students' and teachers' conceptions and science education*. Kiel: IPN – Leibniz Institute for Science Education. <http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html>.
- Gilbert, J. K. (1995). Studies and fields: Directions of research in science education. *Studies in Science Education*, 25, 173–197. doi:10.1080/03057269508560053.
- Gilbert, J. K., & Watts, D. M. (1983). Concepts, misconceptions and alternative conceptions: Changing perspectives in science education. *Studies in Science Education*, 10, 61–98.
- Gilbert, J. K., Osborne, R. J., & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education*, 66(4), 623–633.
- Glaserfeld, E. (1989). Cognition, construction of knowledge, and teaching. *Synthese*, 80(1), 121–140.
- Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching*, 29(6), 611–628.
- Hammer, D. (1996). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions? *The Journal of the Learning Sciences*, 5(2), 97–127.
- Harrison, A. G., & Treagust, D. F. (2000). Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use in grade 11 chemistry. *Science Education*, 84, 352–381.
- Henderleiter, J., Smart, R., Anderson, J., & Elian, O. (2001). How do organic chemistry students understand and apply hydrogen bonding? *Journal of Chemical Education*, 78(8), 1126–1130.
- Justi, R., & Gilbert, J. K. (2000). History and philosophy of science through models: Some challenges in the case of ‘the atom’. *International Journal of Science Education*, 22(9), 993–1009.
- Kuiper, J. (1994). Student ideas of science concepts: Alternative frameworks? *International Journal of Science Education*, 16(3), 279–292.

- Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to western thought*. New York: Basic Books.
- Levy Nahum, T., Hofstein, A., Mamlok-Naaman, R., & Bar-Dov, Z. (2004). Can final examinations amplify students' misconceptions in chemistry. *Chemistry Education Research and Practice*, 5(3), 301–325.
- McCloskey, M. (1983). Intuitive physics. *Scientific American*, 248(4), 114–122.
- Nicoll, G. (2001). A report of undergraduates' bonding misconceptions. *International Journal of Science Education*, 23(7), 707–730.
- Opfer, J. E., & Siegler, R. S. (2004). Revisiting preschoolers' living things concept: A microgenetic analysis of conceptual change in basic biology. *Cognitive Psychology*, 49, 301–332.
- Peterson, R., Treagust, D. F., & Garnett, P. (1986). Identification of secondary students' misconceptions of covalent bonding and structure concepts using a diagnostic instrument. *Research in Science Education*, 16, 40–48.
- Pope, M. L., & Denicolo, P. (1986). Intuitive theories – A researcher's dilemma: Some practical methodological implications. *British Educational Research Journal*, 12(2), 153–166.
- Pozo, J. I., & Gómez-Crespo, M. A. (2005). The embodied nature of implicit theories: The consistency of ideas about the nature of matter. *Cognition and Instruction*, 23, 351–387.
- Schmidt, H.-J. (1991). A label as a hidden persuader: Chemists' neutralization concept. *International Journal of Science Education*, 13(4), 459–471.
- Sjøberg, S. (2010). Constructivism and learning. In E. Baker, B. McGaw, & P. Peterson (Eds.), *International encyclopaedia of education* (3rd ed., pp. 485–490). Oxford: Elsevier.
- Smith, J. P., diSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *The Journal of the Learning Sciences*, 3(2), 115–163.
- Solomon, J. (1987). Social influences on the construction of pupils' understanding of science. *Studies in Science Education*, 14(1), 63–82.
- Taber, K. S. (1994). Misunderstanding the ionic bond. *Education in Chemistry*, 31(4), 100–103.
- Taber, K. S. (1995). Development of student understanding: A case study of stability and lability in cognitive structure. *Research in Science & Technological Education*, 13(1), 87–97.
- Taber, K. S. (1997). Student understanding of ionic bonding: Molecular versus electrostatic thinking? *School Science Review*, 78(285), 85–95.
- Taber, K. S. (1998). An alternative conceptual framework from chemistry education. *International Journal of Science Education*, 20(5), 597–608.
- Taber, K. S. (1999a). Alternative conceptual frameworks in chemistry. *Education in Chemistry*, 36(5), 135–137.
- Taber, K. S. (1999b). *An explanatory model for conceptual development during A-level chemistry*. Paper presented at the British Educational Research Association annual conference, University of Sussex, Brighton. <http://www.leeds.ac.uk/educol/documents/00001429.htm>
- Taber, K. S. (1999c). Ideas about ionisation energy: A diagnostic instrument. *School Science Review*, 81(295), 97–104.
- Taber, K. S. (2000a). Case studies and generalisability – Grounded theory and research in science education. *International Journal of Science Education*, 22(5), 469–487.
- Taber, K. S. (2000b). Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure. *International Journal of Science Education*, 22(4), 399–417.
- Taber, K. S. (2001). Shifting sands: A case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education*, 23(7), 731–753.
- Taber, K. S. (2002a). *Chemical misconceptions – Prevention, diagnosis and cure: Classroom resources* (Vol. 2). London: Royal Society of Chemistry.
- Taber, K. S. (2002b). *Chemical misconceptions – Prevention, diagnosis and cure: Theoretical background* (Vol. 1). London: Royal Society of Chemistry.
- Taber, K. S. (2003a). Lost without trace or not brought to mind? – A case study of remembering and forgetting of college science. *Chemistry Education Research and Practice*, 4(3), 249–277.
- Taber, K. S. (2003b). Mediating mental models of metals: Acknowledging the priority of the learner's prior learning. *Science Education*, 87, 732–758.
- Taber, K. S. (2003c). Understanding ionisation energy: Physical, chemical and alternative conceptions. *Chemistry Education Research and Practice*, 4(2), 149–169.

- Taber, K. S. (2005). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education*, 89(1), 94–116.
- Taber, K. S. (2008a). Conceptual resources for learning science: Issues of transience and grain-size in cognition and cognitive structure. *International Journal of Science Education*, 30(8), 1027–1053. doi:10.1080/09500690701485082.
- Taber, K. S. (2008b). Of models, mermaids and methods: The role of analytical pluralism in understanding student learning in science. In I. V. Eriksson (Ed.), *Science education in the 21st century* (pp. 69–106). Hauppauge: Nova Science.
- Taber, K. S. (2009a). College students' conceptions of chemical stability: The widespread adoption of a heuristic rule out of context and beyond its range of application. *International Journal of Science Education*, 31(10), 1333–1358.
- Taber, K. S. (2009b). *Progressing science education: Constructing the scientific research programme into the contingent nature of learning science*. Dordrecht: Springer.
- Taber, K. S., & García Franco, A. (2010). Learning processes in chemistry: Drawing upon cognitive resources to learn about the particulate structure of matter. *The Journal of the Learning Sciences*, 19(1), 99–142.
- Taber, K. S., & Tan, K.-C. D. (2007). Exploring learners' conceptual resources: Singapore A level students' explanations in the topic of ionisation energy. *International Journal of Science and Mathematics Education*, 5, 375–392. doi:10.1007/s10763-006-9044-9.
- Taber, K. S., & Tan, K. C. D. (2011). The insidious nature of 'hard core' alternative conceptions: Implications for the constructivist research programme of patterns in high school students' and pre-service teachers' thinking about ionisation energy. *International Journal of Science Education*, 33(2), 259–297. doi:10.1080/09500691003709880.
- Taber, K. S., & Watts, M. (1996/2005). The secret life of the chemical bond: Students' anthropomorphic and animistic references to bonding. In J. K. Gilbert (Ed.), *Science education: Major themes in education* (Vol. 4, pp. 238–253). London/New York: Routledge.
- Taber, K. S., & Watts, M. (1997). Constructivism and concept learning in chemistry – Perspectives from a case study. *Research in Education*, 58, 10–20.
- Taber, K. S., Tsaparris, G., & Nakiboğlu, C. (2012). Student conceptions of ionic bonding: Patterns of thinking across three European contexts. *International Journal of Science Education*, 34(18), 2843–2873.
- Talanquer, V. (2006). Common sense chemistry: A model for understanding students' alternative conceptions. *Journal of Chemical Education*, 85(5), 811–816.
- Tan, K.-C. D., & Taber, K. S. (2009). Ionization energy: Implications of pre-service teachers' conceptions. *Journal of Chemical Education*, 86(5), 623–629.
- Tan, K.-C. D., Taber, K. S., Goh, N.-K., & Chia, L.-S. (2005). The ionisation energy diagnostic instrument: A two-tier multiple choice instrument to determine high school students' understanding of ionisation energy. *Chemistry Education Research & Practice*, 6(4), 180–197.
- Tan, K.-C. D., Taber, K. S., Liu, X., Coll, R. K., Lorenzo, M., Li, J., & Chia, L. S. (2008). Students' conceptions of ionisation energy: A cross-cultural study. *International Journal of Science Education*, 30(2), 263–283. doi:10.1080/09500690701385258.
- Thagard, P. (1992). *Conceptual revolutions*. Oxford: Princeton University Press.
- Topper, D. (1990). Newton on the number of colours in the spectrum. *Studies in History and Philosophy of Science Part A*, 21(2), 269–279. doi:10.1016/0039-3681(90)90026-5.
- Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education*, 10(2), 159–169. doi:10.1080/0950069880100204.
- Ünal, S., Coştu, B., & Ayas, A. (2010). Secondary school students' misconceptions of covalent bonding. *Journal of Turkish Science Education*, 7(2), 3–29.
- Vosniadou, S. (Ed.). (2008). *International handbook of research on conceptual change*. London: Routledge.