Alternative conceptions and the learning of chemistry

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Abstract

A great deal of research has indicated that teaching is rarely a matter of introducing learners to material that simply replaces previous ignorance, but is more often a matter of presenting ideas that are somewhat at odds with existing understanding. In subjects such as chemistry, learners at school and university come to their studies already holding misconceptions or 'alternative conceptions' of subject matter. This has implications for subsequent learning, and so for teaching. This article reviews a number of key issues: (i), the origins of these alternative conceptions; (ii), the nature of these ideas; and, (iii), how they influence learning of the chemistry curriculum. These issues are in turn significant for guidance on (a) how curriculum should be selected and sequenced, and (b) on the pedagogy likely to be most effective in teaching chemistry. A specific concern reported in chemistry education is that one source of alternative conceptions seems to be instruction itself.

1. Introduction

Chemistry students usually have some notions which are inconsistent with the concepts that they are expected to learn in their chemistry courses (see §2). This rather general principle has been found to apply across student groups (different school grades, undergraduate education, teacher candidates, graduates), and is, in principle, as relevant to the advanced independent scholar as to those following formal courses of study. This finding is not specific to chemistry: research into the learning of the sciences has reported such alternative understandings from a very wide range of science topics, student groups, and different national contexts. There are good reasons to believe this phenomenon will be found to some degree in any area of human activity that involves learning abstract concepts: the nature of human learning is such that aspects of a learner's existing thinking will often lead to misinterpretations of canonical knowledge (see § 4). The ideas uncovered have been labelled and characterised in a variety of ways (as discussed in §3) but in this review will be referred to as 'alternative conceptions' - that is, conceptualisations entertained by people that are alternative to what is considered canonical knowledge.

This topic has been a major focus of attention in chemistry education as it is recognised that such alternative conceptions have implications for the learning of chemistry (see §5), and so should be taken into account by teachers and those planning the curriculum (see §6). Put simply, if learners come to class holding existing ideas about the topic to be studied, and these ideas are not consistent with what is being taught, it becomes likely that students will either experience difficulties making sense of (and so learning) the intended ideas, or will inadvertently misconstrue teaching leading to distorted understanding.

This review will offer an overview of current thinking about alternative conceptions in chemistry, and their importance for teaching and learning. This will include a consideration of the nature of learners' ideas (§3), and their possible sources (§4); how those ideas influence subsequent learning (§5); and the advice given to teachers who wish to better support student learning by taking learners' conceptions into account (§6). Much of the research into this topic has adopted an approach to thinking about teaching and learning known as constructivism (1-3). The review draws upon key ideas about constructivist perspectives on learning, and in particular the view that learners' pre-instructional conceptions, although they often complicate teaching, are more productively seen as essential (if imperfect) resources for learning than as regrettable obstacles. Research into the nature of human cognition suggests that the development of alternative conceptions is probably both inevitable and indeed often necessary for progression towards understanding of many of the abstract theoretical ideas of science (see §4). This review does not attempt to survey the wide range of alternative conceptions that have been reported, but rather to present some examples and set them within a wider theoretical perspective to demonstrate the nature and educational significance of the phenomenon.

2. Examples of learners' alternative conceptions in chemistry

Research suggests that alternative conceptions can be found in relation to just about any science topic (4, 5), before, during, and even after, the teaching of the topic. A wide range of alternative conceptions have been found in chemistry topics. A small number of examples are offered here as illustrations, but many more can be found in reviews of student conceptions in chemistry (6-9) or the wider literature.

2.1 Some examples of common alternative conceptions in chemistry

- Although there are different types of magnetism, the term is commonly used to apply to ferromagnetism which is only exhibited by a very small number of elements. Yet it is common for younger learners to think that a general property of metals is to be magnetic (10).
- Students, and even science teachers, may have a conception of "chemicals" limited to substances found and used in the laboratory (11).
- Students commonly consider that the product of a neutralisation reaction must be neutral, i.e., neither acidic nor basic (12).
- Students commonly believe that all acids are inherently dangerous (13).
- Undergraduate students have been found to believe that global warming was caused by 'holes' in the ozone layer (14).
- Students at different ages often consider the chemical bond as a store of energy, and think bond breaking releases energy (15, 16).
- Students commonly think that in a chemical reaction there is an active (aggressor) species which forces the other species to react (17).
- Students commonly consider that an atomic nucleus gives rise to a certain fixed amount of force (dependent only on its own charge) which is shared between the electrons around it, and becomes redistributed should the number of electrons change (18).

2.2 An alternative conceptual framework: the octet framework

Sometimes a common alternative conception may be embedded into a more extensive conceptual framework of ideas, as in what has been labelled the 'octet framework' (8). One alternative conception that appears to be very widespread (despite its anthropomorphic nature) is that atoms actively seek to obtain particular electronic structures - octets of electrons or full outer shells - and that this is the basis of bond formation and the driving force for chemical reactions. This was reported among 16-19 year-old students taking chemistry as an elective course in England (19), but findings from that research have been reflected in a range of studies with school and university students in various national contexts (20). This is often described in terms of what the atom 'wants' or 'needs', and sometimes in terms of what it 'feels', etc. (21). Students have been shown to commonly judge some species that would not be feasible in familiar conditions (e.g. Na^{7-}, Cl^{11-}, C^{4+}), as stable if they were considered to have such electronic configurations, and even to consider an excited atom to be more stable than the ground state when an electron was promoted to complete the outer shell (22). In the case of ionic compounds, such as NaCl, students commonly suggest that the ionic bond is (or at least is caused by) an electron transfer from Na to Cl that spontaneously occurs to give the atoms full shells/octets, and that the structure contains ionically bonded ion-pairs held into the lattice by 'just forces' - that is, each Na^{+} ion is bonded to the single Cl^{-} with which it shares a history of electron transfer, and only attracted (i.e., not chemically bonded) to the other five surrounding anions (23). Students may continue to hold this idea even after being taught about the Born-Haber cycle, when they may be aware that the electron affinity of chlorine is smaller in magnitude (c.350 kJ mol^{-1}) than the first ionisation enthalpy of sodium (c.500 kJ mol^{-1}) - and when they should appreciate that the discrete atoms they commonly consider the starting point for compound formation would only be produced if sufficient energy was provided to atomise the metallic sodium lattice and dissociate chlorine molecules.

3. The nature of alternative conceptions

The notion of students holding alternative conceptions of scientific ideas became widely discussed at the end of the 1970s and especially through the 1980s. Major research projects to explore this phenomenon were developed, such as those based in Waikato, New Zealand (24), and Leeds (25) and Guildford (26) in England. The nascent field was influenced by the work on cognitive development of Piaget (27) who had reported many alternative ideas about the natural world found among children, but it represented a shift from Piaget's focus on domain-general thinking being restricted by the stage of cognitive development (and so, generally speaking, age) (28), to the significance of specific conceptions relating to disciplinary content (29). Some of this work (30) was strongly influenced by the psychological ideas of George Kelly (31), who discussed how scientists and others developed unique ways of construing their worlds.

When the prevalence of student alternative conceptions was first reported, initially largely in relation to school level students, it was claimed that learners' pre-instructional ideas were often well-established, committed to, and so tenacious. It was argued that learners' ideas were therefore a barrier to effective teaching, and worthy of careful study (24-26). However, this view was challenged by those who claimed that there were different ways to understand the phenomenon of alternative conceptions (32), and even that the reported conceptions were sometimes artefacts of the research process - that is, that children were often simply responding to researchers' questions by suggesting something that seemed a viable answer based on vague notions, or something romanced in the moment that had no lasting significance (33). Much research has now been undertaken exploring different aspects of people's ideas about chemical topics and many other domains. This does not support a general classification of alternative conceptions as all having the same characteristics, but rather it seems personal knowledge is inherently uneven and multifaceted, and needs to be characterised across several dimensions.

Learners' alternative ideas were sometimes labelled as intuitive theories (34, 35), a term that might be considered an oxymoron (a theory needs to be explicit and applied deliberately; whereas intuition has a tacit basis and offers immediate insights, see §3.5), but which was meant to highlight the way in which children's thinking often had a basis in interpreting experience and could also be widely and consistently applied. The extent to which alternative conceptions should be considered theory-like and framed within a kind of (undisciplined, immature) scientific thinking was a matter of contention. It now seems clear that such debates about the nature of conceptions were inappropriately framed as 'either/or' questions. Indeed, it is not sensible to discuss children's/students'/learners' conceptions or thinking as ontologically distinct from adults'/experts'/teachers' conceptions as if novice and expert thinking comprised a dichotomy. All people can be understood to entertain a wide range of conceptions that vary along a range of characteristics - even if *the profiles* of adults compared to children, or of experts compared to novices, will be quite different.

3.1 Conceptions vary in their match to canonical knowledge

The degree to which the person's conceptions are canonical, that is, match the accepted scientific account, is one dimension that applies in a domain such as chemistry (unlike spheres of activity such as politics or religion where there may be no societal consensus on a single correct way of thinking). Even a mature, well-educated, professional person, with substantial expertise, and much life experience, will hold alternative conceptions. The professional chemist will have conceptualisations of chemical topics that largely match canonical concepts - but may well hold alternative conceptions outside their personal areas of expertise (a chemist's conversation at a dinner party might reveal what others would see as misconceptions about the impressionist painters, the romantic poets, baroque architecture, the global economic crash, and so forth, just as another guest might refer to water as a chemical element, or suggest it would always be dangerous to ingest acids).

The degree of 'alternativism' (31) of personal conceptions can vary considerably. So, for example, the idea that a neutral solution is inherently pH7 can be understood in two ways. Students in introductory chemistry courses will normally measure the pH of an aqueous solution at or close to room temperature where neutrality will be approximately pH7, and so instrumentally this could be considered a good enough pragmatic concept for most purposes - many chemists likely adopt the 'pH7=neutral' notion as a rule-of-thumb even if they keep in mind it should not be over-generalised. However, this may also suggest that the student's concept of how pH links to acidity is primarily heuristic rather than being theoretical (36). The alternative concept that all acids are dangerous most likely involves the adoption of a non-technical notion common in everyday life (acid = dangerous, corrosive liquid) in place of the chemical concept. Here there is a conception of acid with strong associations that are quite different from the ways chemists essentially think about acids (e.g., the Lewis model).

3.2 Degree of commitment to a conception

Peoples' conceptions vary along a dimension of commitment. A person may be extremely committed to a particular way of thinking or more open to shift their thinking. Someone may be aware of a viable way of thinking about some matter without being persuaded it is the best way of thinking about it (and indeed they may fully understand particular conceptualisations, that they dismiss). We entertain many notions without being convinced they are definitely correct. Arguably, a scientist should not absolutely commit to any conception when thinking about the natural world, as science produces theoretical knowledge that is always open to review in the light of new evidence or new ways of thinking about the existing evidence.

Degree of commitment may to some extent be linked to the level of relevant training and expertise, in that in a discipline such as chemistry experts tend to have strong commitment to many basic conceptions considered canonical (37). A professional chemist is probably strongly committed to the principles of conservation of energy and mass, for example (but may have conceptions about economic principles or of the rules of rugby union football to which they have much less commitment). It has been found that many lay people make a distinction between materials that are natural and those that they consider to contain chemicals - so some people wish to avoid foodstuffs that have chemicals in them (i.e., 'chemicals' are all artificial). It is likely that many of those exhibiting this idea would not strongly defend the distinction, which is fairly easy to debunk. However, sometimes people develop strong commitments to alternative conceptions that are not easily discarded: for example the idea that chemical processes occur so that atoms can fill their outer electron shells seems to be retained despite teaching to the contrary (38).

3.3 The presence of manifold conceptions

Another important variable is multiplicity of conceptions. Sometimes a person holds one, and only one, understanding of a phenomenon. However conceptualisation is often more multifaceted: a person may understand the same phenomenon in different ways - which may, or may not, seem inconsistent. A survey that found that not only school students, but also science teachers, tended to see the term 'chemical' to refer only to common laboratory reagents was followed by interviews with some chemistry teachers (11). It was found that some of the teachers initially used 'chemical' in a restricted sense, but when their ideas were explored also suggested the term could apply to all substances. In effect they had two conceptions with the same label, but tended to more readily access and apply the everyday sense. Research suggests that where manifold conceptions exist, contextual cues may determine which version is brought to mind (39).

It is not sensible to commit strongly to two competing and contradictory conceptions. However, if one is not strongly committed to one way of understanding something, it actually makes good sense to be prepared to entertain alternatives that may in time be found to be more productive. Indeed, conceptual change (see §3.7) from alternative conceptions towards canonical concepts, just like theoretical advances in chemistry itself (40), would seem to rely on this possibility.

Moreover, different conceptualisations may seem complementary (rather than contrary), in which case manifold conceptions provide a richer and potentially more applicable conceptualisation. It has even been argued that sometimes chemists have been too ready to adopt particular thinking, so it becomes canonical, and reject alternatives, when the flexibility of maintaining several conceptualisations might have advanced the discipline more quickly (41). Chemistry is a subject which often adopts multiple models that offer complementary insights - for example the range of models and representations used to support thinking about molecules (structural formulae, space-filling models, overlapping atomic orbitals, electron density maps, etc), and so manifold conceptualisation is often appropriate (though in this context this means commitment to a model or representation *qua* model or representation, not as a realistic account of how molecules really are - see §6.4).

So sometimes it may be sensible to commit to a particular conceptualisation, and sometimes not, and people can misjudge this in either direction. One 16-18 year-old student who participated in a longitudinal study showed progress during a chemistry course in term of shifts in the profile of use of several manifold conceptions. He would, in the same research interview explain chemical bonding as electrostatic attraction between charged species; a tendency for a system to minimise energy, and as atoms wanting to obtain full electron shells (42). The student saw these as three distinct explanatory principles (where, from a scientific perspective, the explanations in terms of forces and energy could be considered linked), but also felt it was appropriate to offer the physical explanations and anthropomorphic account of atoms seeking full shells as complementary accounts for the same examples.

3.4 Degree of integration of conceptions

Another dimension concerns the extent to which a particular conception is embedded within wider frameworks of related conceptions. Some alternative conceptions are largely 'stand alone' ideas, with only weak linkage with other ideas a person may have. An example might be the conception that children have often developed that metals are magnetic (i.e., what a chemist would call ferromagnetic), that is, that being magnetic is a general property of metals (10). Whilst the child would have other conceptual links for both metals and magnets, these do not rely in any sense on this specific alternative conception.

However, sometimes a particular conception becomes part of an interlinked conceptual framework of ideas (see §2.2). So a student who thinks that chemical reactions occur so that atoms can obtain full electron shells (20) will often also think that there are two main types of bonding (covalent and ionic, which can be readily explained in terms of forming full shells) whilst other bond types are just variations on those main classes (metallic, polar, dative) or not really proper bonds (van der Waals, solvation). Hydrogen bonds are often misconceived as covalent bonds to hydrogen. The student who has developed a conceptual framework around this principle will often also think that within ionic structures such as NaCl there are identifiable ion-pair units acting as pseudo-molecules (as ionic bonding is falsely identified with an imagined electron transfer event between two atoms - even when students have prepared NaCl themselves by neutralisation, see §6.2), and these ion pairs are the main solvated species in solution. The student may also think that there are large jumps in successive ionisation energies of an element corresponding to different electron shells/principle quantum number (which is the case), because it is intrinsically more difficult to remove an electron from a full electron shell (which is not so, see §6.2 for a suggestion on challenging this idea).

3.5 Tacit knowledge elements

A final dimension that is important is the extent to which a learner's ideas are explicit rather than tacit. Explicit conceptions can be accessed deliberately for conscious reflection, and verbalised and/or visualised. However, much of our cognition relies on intuitions that are the result of knowledge elements represented in the brain, and which are active in cognition, albeit preconscious cognition. It has been suggested that humans in effect have two systems for thinking - a slow, but explicit system and a much faster intuitive system (43). Our intuition allows us to make a quick decision (which can be important sometimes) but not to interrogate our rationale, as the outcome of intuitive thought is a sudden insight: so we come to an answer or decision, but cannot logically justify it. Science puts great importance on the justification of knowledge claims, so relies on the deliberate conscious type of thinking - but many scientific breakthroughs have arrived as a moment of insight to be later validated and explained (44). The chemist and philosopher Polanyi (45) drew attention to the role of tacit knowledge in the practice of science, something later demonstrated in sociological studies of how science actually proceeds (46).

When students apply their explicit alternative conceptions they are aware of the basis of their responses, but when operating with implicit knowledge students may rather offer answers to questions which 'feel right' to them (47), as they are making intuitive judgements rather than consciously thinking through an answer. If pushed for an explanation, a student may be able to offer a post-hoc justification of their suggested answer, but this does not reflect their original thinking process which occurred outside conscious awareness.

3.6 Degree of commonality of alternative conceptions

Another important variable is less about the inherent nature of a particular conception, than its frequency in a population. Each student is somewhat unique, having built their conceptions of the world from an idiosyncratic set of personal experiences, and detailed exploration of any student's ideas is likely to reveal unique, or at least rare notions. That said, humans have much commonality in the general nature of their perceptual and cognitive apparatus, live in the same physical world, and are socialised within particular cultures. Existing in communities means that experiences are discussed and so an individual's thinking is somewhat socially moderated. This is a common part of the human experience in the family, tribe, workplace, etc. - education is a particular, formal, strand of this.

In my own work with English college students (16-19 year-olds, mostly working towards University admission) I sometimes found a study participant would present something that I'd never come across with any other student. I will offer two examples which only came to light because I did spend time individually interviewing (volunteer) students. One is fairly trivial, but sticks in the mind. One of my students used the term 'electron shields'. From the context, this was a synonym for electron shells. Once I had spotted this, I then noticed he was using this term consistently. In other words I had initially heard 'electron shield' as 'electron shell' (and would presume that his peers also failed to notice, and that he, thinking the correct term was 'electron shield', was habitually hearing 'electron shell' as spoken by his teachers and peers as 'electron shield'). Much of the interpretive processing in cognition is automatic, so we do not always easily notice things that do not fit with our expectations: an expectation in effect 'corrects' an anomaly before it reaches consciousness. Only when listening carefully enough to attempt to transcribe an interview verbatim, so paying attention to the individual sounds, did this become apparent.

That particular example is somewhat trivial - and indeed the 'shield' metaphor (we talk of 'shielding' when considering atomic ionisation for example) was not intrinsically flawed as the electron shells are no more literally shells than they are shields. Another example, however, concerned a conceptual matter rather than nomenclature, and took longer to diagnose. I interviewed this student after a term of her two-year course, at the end of the first year, and then again shortly before the terminal examinations. In each interview there were indications that the student was getting some, but only some, chemical formulae wrong, but it was less clear why. Only when analysing the third interview did I recognise a common pattern across her correct and incorrect responses, relating to stoichiometry. Listening to her explanations for her calculations it became clear that she had a different meaning to the + and - symbols used to denote ions such as Na^+ (48). I was then able to provide some feedback on this before the chemistry examination. This student had managed to almost complete her college chemistry course without her, or anyone else, realising that she understood and used the charge symbols in a completely different way to her teachers, to her peers, and to her textbooks. Had she not volunteered for a sequence of in-depth interviews, it seems very unlikely this apparently idiosyncratic conception would ever have been diagnosed.

Other conceptions seem very common - or at least, many students hold alternative conceptions that are very similar. The idea that reactions occur to allow atoms to fill their electron shells or form octets seems to be very widespread among students in various parts of the world (20). The precise language used to express this, and the range of application of the idea, and the extent to which it is used consistently or interspersed with more canonical ideas, can all vary. However, the principle that much chemistry is explained by atoms needing to get the right number of outer shell electrons is very commonly expressed by students of chemistry.

3.7 Conceptual change

If students commonly have conceptions that are inconsistent with canonical chemical concepts then part of the work of the teacher or lecturer can be considered as facilitating, encouraging, or perhaps engineering, conceptual change. Conceptual change is a term that is often used in research reports to refer to shifts from alternative to more canonical ways of thinking (49): however, strictly conceptual change refers to any change in a person's conceptual understanding, and it is possible to characterise different forms of conceptual change (50). So this would include shifts from alternative to canonical ways of thinking, but also (in principle) changes in the opposite sense. It also encompasses shifts in the range of application of a concept (that is, the 'same' concept is actually modified when its range of application changes), or progression in the sophistication of understanding of a concept, or changes that involve the differentiation or integration of concepts, or the acquisition of new facets to a concept.

So, examples of conceptual change that would be desirable in chemistry learners at specific points in their development might include, *inter alia*:

- Acquisition of a concept of entropy;
- Expansion of the orbital concept to encompass molecular as well as atomic orbitals;
- Moving beyond seeing metal/non-metal as a dichotomous classification to appreciate the electronegativity scale;
- Differentiating the concept (and so category) of metals to include a new concept (and subcategory) of transition metals;
- Acquiring a notion of the 'expansion of the octet' in period 3 that changes understanding of the application of the valency concept for P, S, and Cl ;

- Shifting beyond seeing reactions as simply reversible or irreversible to appreciate that all reactions can be conceptualised in terms of equilibria;
- Subsuming bonding in aromatic compounds, graphite, and metals, under a broad concept of delocalisation
- Rebranding an existing concept of 'magnetic' as ferromagnetic, to encompass diamagnetism and paramagnetism within a more general concept of magnetic.

Clearly many more examples could be offered - but the point is that forming a new concept or correcting an alternative conception are not the only kinds of conceptual change work being undertaken in chemistry classes. There is a good deal of literature discussing conceptual change in science education, and conceptual change has been described and characterised in various ways (51). A common distinction drawn is between assimilation and accommodation - between adding something to existing conceptual knowledge (learning an additional example of an element, or a metal, or an oxidising agent, etc.), and modifying existing knowledge - such as abandoning the idea that bonds store energy and appreciating that bond-breaking is always an endothermic process (52). The terms are drawn from Piaget's theory of cognitive development (53), where such development was posited as always occurring through a process of assimilation-disequilibrium-accommodation-equilibration, so any addition requires some level of restructuring of the prior system. The extent of such restructuring varies. So although a student discovering there is an element previously not met, say manganese, does not fundamentally change their 'element' concept beyond being able to give an additional example; learning about oxidation states can add to an understanding of oxidation as process, but also significantly modifies it (e.g., the range of application of the concept 'oxidation' is considerably extended, to include examples of reactions previously excluded).

A classic paper suggested criteria for when conceptual change might occur: that there must be dissatisfaction with existing conceptions, and a new conception must seem intelligible, plausible, and fruitful (54), but later work suggested a wider 'conceptual ecology' needed to be considered including affective considerations (motivational factors) and metacognition (self-regulative skills that involve the monitoring and evaluation of one's thinking) (55). One perspective on conceptual change saw concepts as organised in ontological trees where conceptual change requiring moves between different tress was problematic - for example if a child considered heat as a type of substance, changing to understand heat in terms of a process instead is very difficult (56). In extremis, existing alternative conceptions need to be supplemented by new distinct scientific conceptions, that with familiarity and regular use will come to be habitually used instead (40). In this model, the alternative conceptions is not itself modified, but just falls into disuse. If the original conception was well-established, this leaves open the possibility that if the scientific option is not sufficiently reinforced and consolidated, it may no longer be readily brought to mind, and there may later be a regression to activating the alternative conception (38). Another perspective, informed by Kuhn's work on shifts in scientific thinking (37), suggests individual concepts are usually embedded in more extensive framework theories, which - in effect - protect them from ready change (57).

The examples of potential conceptual changes during chemistry learning offered above suggest no one simple model of conceptual change will easily encompass all forms of change (and it is worth noting that theorists seem to most commonly work with examples of conceptual change from physics). Conceptual learning in chemistry may involve adding additional models or representations to an existing concept (58), and progression may be recognised as shifts in the profile of use of different layers or facets of complex concepts (42, 59). Just as students' conceptions vary in their characteristics in a number of ways (§3.1-3.5), so conceptual change cannot be sensibly assumed to be all of a kind.

4. Acquiring personal conceptions

A naïve view of teaching that novice teachers may bring to their work (i.e., an alternative conception about teaching) is that the teacher's role is to move students from a state of ignorance about matters that they have not been taught about, to a state of knowledge. This is an easy position to adopt in chemistry teaching:

if students have not previously been taught about reaction profiles, transition metal complexes, d-level splitting, or whatever, then it may seem reasonable to assume that the teacher is directing instruction within some kind of conceptual vacuum. Yet the body of research referred to above suggests that even in such topics where we would expect most students to have no prior knowledge, learning of canonical material seems to be influenced by existing conceptions and established ways of thinking. It is therefore important to consider how students may develop their alternative conceptions.

4.1 The acquisition of implicit knowledge

In effect, the issue is how humans acquire knowledge - in the sense of the various conceptions they entertain, whether canonical or not (60). This is a complex topic, but there are two rather different general processes involved in learning that work rather differently (cf. §3.5): the first of which operates automatically without direct conscious control. Human cognition is to some extent 'programmed' to unfold in a particular way through interaction with the environment (53). That is, we have evolved to have brains that automatically make sense of our experience - something that clearly has survival value in terms of supporting action in the world. Even young babies have 'expectations' about certain regularities in the physical world (61) - so for example, if a magic trick is played such that some solid object in view appears to disappear, then they react as if surprised. (Researcher's tend to make inferences from the duration of babies' stares as they have no language to communicate their thinking.) A normally developing person comes, through acting in and experiencing the world, to adopt certain basic conservation principles - such as appreciating the amount of material in a sample is not changed when its shape is changed or it is divided into parts (53).

Such knowledge is developed by automatic processes that occur pre-consciously, and can be understood as abstracting commonalities from experience (pattern spotting) that then act as a basis for expecting future experience to fit this pattern. In young children these processes begin long before they have access to language, for example, but this form of cognitive processing continues throughout life. The 'knowledge' elements developed then act at the intuitive level within perception and cognition, as 'black boxes' not open to conscious interrogation. Despite their inaccessibility to introspection, these expectancies about the world can have strong effects in formal learning. An influential model (largely developed in the context of studying physics learners) refers to these knowledge elements as phenomenological primitives, or p-prims (62), and it is argued that much of our accessible conceptual thought is in effect developed by recruiting such tacit elements (63). It has been argued that the brain automatically 'boot-straps' more explicit and mouldable levels of cognition from available implicit knowledge elements through a process of re-representation (64). This area of research suggests that even though learning chemistry requires an explicit engagement with a formal knowledge system, the cognitive apparatus used is very much shaped by implicit knowledge a person is not even aware they have.

The p-prims approach is also sometimes known as 'knowledge-in-pieces' (65), emphasising the idea that the implicit knowledge elements act as kind of conceptual toolkit - or perhaps better, a kind of conceptual identikit set (that is, like the set of facial components used by police to help witnesses build up an image of someone seen at a crime scene) - from which elements that fit specific situations are selected. This model may be contrasted with the idea that people develop what have been called 'framework theories' (66) - which are naive, but largely stable and coherent, networks of explanatory ideas that are systematically used to interpret experience in some domain. These two perspectives need not be at odds (17): if the infant's knowledge originates in implicit knowledge elements it will initially be little more than a collection of discrete intuitions about the world, but over time these will be recruited into more systematic resources (e.g., conceptual frameworks that may be alternative or canonical) that become widely used in particular domains. A mature person has many such derived conceptual structures they regularly use in familiar contexts, but also their set of p-prims that are activated when a situation or experience does not seem to fit into one of the more elaborated frameworks.

4.2 Cultural facilitation of learning

Modern humans also have a totally distinct way of acquiring knowledge, in terms of cultural tools such as language. The existence of culture allow individuals to short-cut much of the work of developing scientific knowledge. Modern chemistry is based upon several centuries of experimental and observational work, carried out by generations of chemists. A student today does not have to directly work through the vast catalogue of past experiments (including many dead-ends, and much that modern risk assessment would not allow) to understand modern chemical concepts. By using language and diagrams, much can be presented and explained concisely. However, there is a limit to the ability to communicate ideas purely through symbol systems (such as natural language, diagrams, graphs, etc.) in that not only must the learner have sufficient competence in using the symbolic systems (e.g., a spectrum is inherently just a pattern of lines), but they must also have resources to make sense of the ideas.

Clearly many higher level conceptual ideas build on existing conceptual knowledge, but all conceptual knowledge has to be ultimately ground in experience (see §4.1). That is, abstract knowledge is made sense of in terms of direct experience of the physical world. This can be seen in the extensive use made of physical referents (on top of, at the bottom, inside, larger, etc.) that are commonly applied metaphorically to abstractions (67). References to a 'higher energy level' or a 'ground state' draw upon relations we all understand from direct experience of the physical world. Whereas many metaphors adopted are more obvious (the notion of an 'excited' state draws on a different kind of experience that it is assumed we all share), these physical metaphors are so basic to our making sense of experience that they tend to go unnoticed. As teachers we tend to assume it is self-evident how one energy level can be 'higher' than another and are unlikely to feel we need to explain the metaphor - even if referring to a graph drawn on a horizontal page it is taken as obvious what 'higher' means. (A reader may counter that we can put numbers on energy levels, but of course the number -3.4 is only 'higher' (rather than greater, more positive) than the number -13.6 in a metaphorical sense.)

The influential psychologist and educational thinker Lev Vygotsky long ago emphasised the role of culture and socialisation in the sharing of 'scientific' concepts, which were contrasted with 'spontaneous' concepts which developed without any deliberate formal instruction (68). Where Piaget's work had focused on spontaneous concepts developed in interaction with the environment by a child who had reached a stage of development that made them ready for that learning (69), Vygotsky and his collaborators put much more emphasis on the historical development, and subsequent sharing, of ideas within a culture (70, 71). However Vygotsky also emphasised that although these two type of concepts were distinct in nature and origin, they interacted in conceptual development. That is, formal taught concepts provided the language for talking about and sharing one's spontaneous concepts, and such 'everyday' concepts provided the experiential base for making sense of scientific concepts. Vygotsky's model implies that the concepts people operate with are usually melded concepts, the hybrids deriving from the interaction between scientific and spontaneous concepts (60). Just as early human ancestors (or a young child today) will have formed spontaneous concepts but lacked any language to support reflection or sharing (and so dialogue with others); a student may acquire a formal definition (e.g., an element is a substance that cannot be broken down to simpler substances by chemical means) without making sense of it - which is known as rote learning. Ausubel (72) distinguished between rote learning (learning by heart without understanding) and meaningful learning where material to be learnt was recognised as being relevant to, and was then related to, prior learning. To understand and be able to apply a new concept, it needs to be learnt in a meaningful way, which means in terms of existing conceptions.

When a learner comes to chemistry classes they will be operating with melded concepts that cannot be said to have a single source, as the nature of human cognition is to be constantly interpreting new experience in terms of the abstractions previously derived from prior experience, both to make sense of present experience, and, if indicated, to modify current knowledge. The human cognitive apparatus acts as a system for developing and updating an internal model of the world to allow us to make sense of and so act in the world (60): so human learning tends to be interpretative (making sense of the new in terms of existing conceptual resources); incremental (as the system has limited working memory capacity for handling novel information); and, consequently, iterative (73).

4.3 Sources of alternative conceptions

One key source of a person's conceptions is the set of intuitive knowledge elements that automatically fit perceptions to familiar patterns of experience, and so shape how experience is understood (see §4.1). These resources are independent of domain, so the same general abstracted patterns may be recruited to make sense of different areas of experience.

Another source of a person's thinking comprises of beliefs they are exposed to in their social environment. If they regularly hear references to acids being dangerous, or to there being a hole in the ozone layer, or the term 'chemical' used in a prerogative sense ("I choose organic [sic] foods because they have not been exposed to chemicals"), then they will tend to acquire conceptions from the social milieu which they will at least entertain (and which may provide a unitary conception until formal teaching offers the plurality of a canonical alternative).

Language can be a source of alternative conceptions in another sense. Although people within a community 'share' language, everyone has a somewhat idiosyncratic personal set of meanings and associations for many terms (74). Learners may often have impoverished or distorted meanings for language used in teaching. This has been found in chemistry both in terms of the technical terminology of the subject, and in terms of the basic terminology of academic discourse that may be used in instruction - students my misunderstand what is intended by terms such as negligible, converse, converge, etc. (75). A person may therefore listen to statements that are technically correct, yet 'hear' something different.

Moreover, language is often used in metaphorical, poetic, etc, senses. The speaker is aware of the intended meaning, but uses metaphor, analogies, similes, etc., that (for the speaker) communicate the idea. The listener has to interpret the meaning but may not infer the intended meanings. The term 'reaction' (i.e., re-action) may imply a response to something, and reinforce the conception that a passive substance is reacting to an active substance. An extreme form of this is the existence of dead metaphors. As suggested above (§4.2), human thought often develops metaphorically, and sometimes these metaphors becomes fossilised (so to speak, i.e., using a metaphor) in language. For example, the notion of electric charge, as in the charge on an ion or electron or nucleus, is said to derive from the idea of charging a gun with gunpowder. Something that at the time was novel and not well understood (i.e. electricity) was discussed in terms of something that was (then) familiar from everyday life - a charge was an amount of something substantive, and the label became used also to refer to an amount of something more tenuous.

Nowadays, students are likely to be familiar with the notion of electric charge, but not to have any experience of using gunpowder to charge weapons, so there is little educational consequence. However, another example might be how covalent bonding is often described as being the sharing of electrons. The process by which molecules are bound is described in terms of a very human activity - as when two people share a house or a pizza. To chemistry teachers this term is likely a dead metaphor. It is such a familiar trope, that a chemist seldom stops and thinks about how 'sharing' is to be understood in the context of bonding - and indeed research chemists do not find it incongruous to retain the term 'electron sharing', without clarification, in highly theoretical accounts of bonding (76). A student first meeting this expression will make sense of it in terms of their existing associations of sharing - which may not be especially helpful in understanding the chemical concept. Learners may also infer implications from language that were not intended. An example would be the common alternative conception that the product of a neutralisation reactions is always neutral (12): not an unreasonable implication to take from the choice of term.

As the neutralisation concept is usually introduced in the context of strong acids reacting with strong bases, and students may be asked to find an endpoint using indicator paper to check for pH7, this inference is then reinforced. Their early laboratory experience of such reactions may also lead them to think that strong acids (always) have pH1, and that in aqueous systems neutrality is defined as pH7. Commonly used indicator papers and colour charts show acids with a pH of zero and lower as pH1, so that this appears to be a limit, and means modest dilution of a strong acid (perhaps actually initially of pH -0.5) does not appear to change its pH. The variation of pH of pure water with temperature is seldom considered in introductory teaching, so the simplification that pH7 is neutral may be adopted as a definition rather than an empirical fact under particular conditions.

This leads to considering another source of students' alternative conceptions - teaching. Teachers may themselves sometimes have non-canonical understandings, and this is not meant to suggest there are some teachers with poor subject knowledge (even if that may be so), but simply given the complex and iterative nature of human learning as described here, and the broad range of a chemistry curriculum, it is almost inevitable that many teachers will themselves hold some alternative conceptions within their own subject specialism, and studies that have been carried out with teachers and teacher candidates have found this - for example in relation to chemical equilibrium (77), the gas laws (78), the mole concept (79), atmospheric chemistry (80), chemical change (81), and ionisation energy (82).

Whilst teachers inadvertently presenting chemistry that is incorrect will be a factor in some cases, the need for learners to interpret what they are being told and shown in terms of existing conceptions is likely a much more frequent issue. Related to this may be a limited sophistication in appreciating the role of models and representations in science (83). Scientific models are not meant to necessarily be realistic (a totally realistic model ceases to be a model), but students may not appreciate this and may adopt models and representations used in teaching as if intended as definitive accounts: so presenting atomic structure in terms of concentric electron shells may lead to students assuming that is how atoms actually are, which can be a problem for subsequent conceptual development.

Bachelard (84) pointed out that scientific ideas and representations carry the imprint of philosophical thought prevalent at the time they were formed and developed, and in a similar way learners understand concepts in the light of their own development towards epistemological sophistication, and this becomes 'fossilised' in their thinking with those concepts. So chemistry graduates have been found to retain and preferentially present the same models and descriptions of chemical bonding (shared electrons, sea of electrons, etc.) as school students, even though they have learnt, and may also be able to apply, more sophisticated models (85).

5. Implications of alternative conceptions for learning

This description of the nature and origins of students' alternative conceptions draws upon a perspective that has been extremely influential in science education, known as constructivism - a term that reflects the idea that knowledge acquisition is necessarily a process of construction, building up from component parts. Complex abstract ideas cannot simply somehow be transferred or copied wholesale from one person to another. The teacher's concepts have acquired their nuanced meanings over extended periods of study and are deeply embedded in extensive networks of associations, and - no matter how skilled the teacher - cannot be directly replicated in students' minds. Early work into student conceptions was organised around a number of principles, some of which have been characterised (29) as:

- Learning science is an active process of constructing personal knowledge
- Learners come to science learning with existing ideas about many natural phenomena
- The learner's existing ideas have consequences for the learning of science
- It is possible to teach science more effectively if account is taken of the learner's existing ideas

It is recognised that there are a number of possible outcomes of interactions between teaching and prior conceptions (86). Extreme cases include the learner adopting the new teaching as intended, and no longer employing their prior conceptions; or the learner retaining their prior conceptions, and (in effect) ignoring teaching. Whilst approximations to these extremes sometimes occur, it is also possible that the student learns the new knowledge alongside their prior conceptions (such as the student referred to above who came to appreciate bonding could be understood as an interaction between charged particles, but without this requiring the abandonment of the alternative understanding that it was also the outcome of atoms seeking full shells); or that the student interprets new information in terms of their existing alternative conceptions, and so distorts the intended meaning to make it coherent with existing understanding; or that the outcome is a kind of compromise where there is both some shift in the prior conceptualisation to accommodate new teaching, but also some distortion of that teaching in making sense of it, resulting in a conception which is intermediate between the prior understanding and the target knowledge.

As one example, students commonly hold a so-called 'conservation of force' conception that an atomic nucleus gives rise to a certain fixed amount of force which is shared between the electrons around it. Students will suggest that when an atom is ionised, the removed electron's share of the force is redistributed making a subsequent ionisation more difficult (18) - which is consistent with the empirical findings. Formal teaching of the scientific Coulombic model may persuade students that the jumps in ionisation energy linked to different shells are indeed due to an electron closer to the nucleus experiencing more force, but retain the notion of redistribution of force to explain the increases in successive ionisation energies within the same electron shell.

5.1 The challenge of class teaching

What this means for the lecturer or classroom teacher, is that offering a technically correct, well constructed, and apparently clear, account of the chemical concepts to be taught does not give an assurance that students will understand them as intended, and so learn the material canonically. Moreover, as every student in a class has a somewhat idiosyncratic set of resources for interpreting teaching (their existing concepts, their understanding of technical and non-technical language, their personal associations for metaphors, similes and analogies used, their level of appreciation of the affordances and limitations of models and representations, etc.) it is often likely that different learners will make different sense, and take away different learning, from the same teaching. All experienced teachers know that happens, and the considerations discussed above make it inevitable much of the time. It is easy to dismiss this as students having different levels of intelligence and motivation, and as some working harder than others. Clearly such factors are at work, and the students have to take some responsibility (especially in higher education), but the teacher also has a duty to teach in a way that best supports student learning.

This constructivist perspective on learning then has major implications for planning teaching. A consideration of the prior learning that should be assumed for a topic (87), and analysis of the material to be taught to make decisions about such matters as sequencing, including links to prior knowledge, depth of treatment, appropriate pace, is not sufficient. Students bring to class prior learning that may be deficient in relation to (or may sometimes exceed) that nominally expected for the course, and each have their own personal set of existing alternative conceptions, and idiosyncratic set of resources for interpreting teaching - so it is inevitable that tightly scripted lessons (as many university lectures may be) will leave some students confused, and lead to various misinterpretations, regardless of how well crafted the presentation is.

Students will not be aware when they have misinterpreted teaching. Where students have particular alternative conceptions with high levels of commitment, they may be so confident in their existing understanding that they do not critically examine their existing ways of thinking. For example, when students (who had been taught chemical ideas about reaction energetics) were asked to explain the reaction $H_2 + F_2 \rightarrow 2HF$, they commonly responded in terms of the 'needs' of individual atoms to achieve full electron shells - even though the reaction equation they had been given made it clear the reactants were already molecular (88). Teachers need to bear in mind that the degree of coherence and interlinking between conceptions varies (see §3.4), and is generally more limited in novices than experts, and not draw inferences that demonstrated knowledge excludes apparently inconsistent conceptions. So just because students know that they safely ingest citric acid and ascorbic acid, and that their genetic material is deoxyribonucleic acid, this may not prevent them readily activating a long-established conception that all acids are dangerous.

5.2 Working with students' thinking

A well recognised educational principle, popularised by Ausubel (89), is that the most important factor in teaching learners is to find out what they already know, and then to teach them accordingly. Research has shown that careful exposition of student thinking about chemical topics can reveal complex, subtle, and multifaceted conceptions (58, 90), and it is clearly not feasible for teachers to engage in such exposition as a routine matter; nor indeed, to apply such detailed knowledge in planning class teaching. However, as a general principle, the more the teacher takes into account students' existing conceptions, the better position they are in to support student progression towards canonical concepts.

It has also become recognised that given the way in which human learning appears to function, as outlined above, major conceptual shifts tend to take place over extended periods of time. As understanding abstract ideas (as many concepts met in chemistry are - periodicity, oxidation state, resonance, reaction mechanisms, entropy, etc.) relies upon making sense of them in terms of what is already familiar, it is not going to be possible for a young child relying mainly on spontaneous concepts to make good sense of such ideas. Rather, one needs to accept a progression with various 'intermediate conceptions' acting as 'stepping stones' towards the more formal concepts (91, 92). This has become the basis of an active area of research, mainly focused at middle and high school levels, on 'learning progressions' (93-95). From this perspective, a student's alternative conception of some chemical idea can sometimes be best seen as a potential resource for further progress. Even at university level, the 'learning demand' (96) - the difference between current conceptions and target knowledge - may often be too great for many students to directly shift to canonical conceptions without passing through intermediate steps.

6. Pedagogy that takes into account alternative conceptions

That effective chemistry teaching takes into account the students' current thinking, including any alternative conceptions they may hold, represents a fairly simple principle; yet applying the principle within pedagogy is only straightforward in the exceptional context of a tutor working with a single learner. In that situation, teaching can take the form of a kind of Socratic dialogue (97) with the tutor teaching through the process of probing student thinking in discrete steps to suggest leading questions designed to channel thought towards canonical concepts. Whilst that is less viable in a group or large class teaching context, the notion that good teaching has the quality of dialogue has strong support (98, 99). Dialogue implies that there is active consideration and comparison of alternative viewpoints or perspectives. As well as the issue of working with a range of different students at one time, there is also the basic question of what pedagogy designed to take into account learners' thinking actually comprises.

This section therefore explores two issues: how the teacher of a large class knows what students are thinking, and how they might design their teaching accordingly. In some respects appropriate pedagogy is more readily adopted in school classrooms in educational contexts where it is normal practice for lessons to be divided into a series of episodes where teacher presentation is alternated with student activities, and where the teacher will talk with the students individually during lessons as they work and so have opportunities to check their understanding. Such a context offers scope for incorporating elements of appropriate pedagogy. Instruction based on the teacher lecturing, as is still often found in many university courses (and sometimes in some school systems as well), may require the lecturer to make some small adjustments in terms of lecture structure, and some more substantive shifts when thinking about presentation of subject matter, to adopt indicated pedagogy.

6.1 Diagnosing student thinking

A first step is for the teacher to be aware of students' *likely* alternative conceptions when planning teaching. As acknowledged above, a programme of in-depth interviews with individual students, as is often found most productive in research to elicit student conceptions (100), is seldom feasible in class teaching contexts. However, there are less labour-intensive sources of information that can be useful. One resource is the primary research literature which reports on the findings of studies into student thinking, or reviews and digests of that literature (5, 8, 9). Although alternative conceptions can sometimes be very idiosyncratic, research has uncovered common alternative conceptions in many topics.

This enables the teacher to identify the most likely points at which some specific teaching input might be needed. Knowing that, for example, students (16) - even at university level (15) - commonly think that chemical bonds store energy, allows the teacher to recognise one likely focus where students' existing thinking may be a barrier to understanding, or is likely to led to learners misinterpreting teaching. The teacher can choose to explicitly address such points in a presentation.

It is also possible to use a form of diagnostic assessment designed to help identify where students have common misconceptions. There are various diagnostic instruments (101) and concept inventories (102) available in some topics, suitable for using with students at the start of a course or topic. These include objective items (such as multiple choice questions), sometimes with several levels - such as a first tier asking a 'factual' question, and a second tier where the respondent select their reason for their choice in the first tier (103), a design developed as part of a systematic approach to instrument construction informed by analysis of the chemical subject matter and research on student thinking (104). These may even be available digitally, allowing a computer to quickly analyse responses and compile a report. One concept inventory designed for use at the start of university chemistry was informed by research reporting alternative conceptions in a range of topics included in general chemistry courses: the particulate nature of matter; properties of atoms; bonding; gases; liquids and solutions; conservation of mass and atoms; symbols; equations, and stoichiometry; chemical reactions; heat and temperature; phase changes; and macroscopic versus atomic and molecular properties (105). Alternatively there are resources to support in-class activities that offer diagnostic information. At school level these may be set up as group work that encourages students to explain and compare their thinking with peers before the teacher seeks to survey ideas across the class. Some activities are suitable for quite young students, for example discussing concept cartoons - usually showing people offering different views and explanations relating to a phenomenon. These are designed to reflect both canonical thinking and common alternative conceptions as starting points for discussion. While group-work of this kind may seem out of place in the university lecture hall (but could certainly be used in tutorial groups and examples classes), it is possible for a lecturer to include quizzes along the same lines in lectures. The lecturer stops at particular points in the lecture to ask the class an objective question to either check essential prerequisite knowledge, or to see if the present teaching is being understood as intended. Again research literature can suggest possible distractors to include in a question that are likely to resonate with students' alternative conceptions. The aim is not to trick the student: if the distractor seems the most appropriate response here, then the alternative conception it is activating is also likely to be activated in the context of an examination. For example, considering the example above, students can be asked to select one of:

A Energy is released whenever a bond breaks

B Energy is released whenever a bond is formed

C Energy is only released when some bonds, such as high energy phosphate bonds, break

D Chemical bonds store the energy provided as activation energy to initiate reaction

Issues that are important in designing summative assessments used to grade students, such as avoiding potentially overlapping response options, or imprecisely or ambiguously worded responses, are less critical in diagnostic items used in class as starting points for exploring or clarifying ideas.

Some universities have clicker systems (response units with a series of buttons for answering multiple choice questions) available that allow an immediate visual presentation of the profile of responses so the lecturer and class can see the (anonymous) support for different answers (106). The lecturer is then able to decide if there is a need to retrace steps, reiterate assumed prior knowledge, or explore particular sticking points with the class, before proceeding. A show of hands can otherwise be used, although this has potential for embarrassment (a student suspecting they may be the only respondent giving the wrong answer - even if that would seldom happen if response options are thoughtfully chosen) and some students may change their initial response to join the most popular option - which if not correct, as least puts them in a crowd. This can be avoided to some extent by not seeking individual responses, but asking students to take (say) three minutes to work in groups of three students and then requiring the groups to vote. Even when a clicker system is available, it may be more productive to ask students to take a short time out to discuss a question with their neighbours before the vote. Justifying an answer to peers requires students to think about their ideas - and to seek a rationale to support their intuitions.

As well as deliberately building-in opportunities for diagnostic assessment (to check prior knowledge and understanding) or formative assessment (to check how teaching is being understood), the teacher or lecturer can learn a great deal about students' thinking by paying attention to the questions students ask in, or after, classes, and through informal discussion (for example if a student seeks to talk to a lecturer between classes). Experienced teachers and lectures can build up extensive knowledge of the alternative conceptions and difficulties that their students have demonstrated in particular topics.

6.2 Responding to alternative conceptions: working for conceptual change

When research into learners' alternative conceptions started appearing in the literature it was common to suggest that teachers needed to 'challenge' these conceptions, which was only possible once they had been elicited (107). It was sometimes assumed that learners' conceptions would be naïve and could easily be supplanted - after all canonical principles and concepts are canonical because they have the authority of science, based on a good deal of investigative, empirical chemistry. However as the more complex and diverse natures and derivations of student conceptions (see §§.3-4) became apparent it was recognised that simply seeking to correct alternative conceptions by pointing them out and presenting the canonical concept would often not be sufficient. For example, once students have developed the idea that chemical reactions occur, and bonding forms, to allow atoms to fill their electron shells, they commonly continue to offer explanations of this kind in spite of teaching that contradicts this and offers more canonical alternatives. In these situations the teacher has to acknowledge that the desired conceptual change (see §3.7) is substantive (108), and that this may be a slow process that requires prolonged engagement with the canonical ideas to provide (a), initially, sufficient familiarity and understanding to allow mental exploration of the potential implications of the ideas, and (b), then, over time, opportunities to work with arguments for, and applications of, the canonical scientific accounts.

Presenting the canonical view as a matter of authority might persuade learners at the time that they need to shift their thinking, but even if the presentation is supported by apparently convincing arguments, this does not make it likely that students will bring to mind and apply the canonical understanding in appropriate contexts days, weeks or months later, when they already have a well-established alternative that they can use to make predictions, give explanations, or answer test questions (109). The human brain is a highly associative apparatus, and well-rehearsed and familiar concepts are more readily accessed and applied than less consolidated ideas - even if those less established ideas are objectively superior. One aspect of effective pedagogy then, when responding to well-established alternative conceptions, is that it does not consist of a discrete teaching event - but rather takes place over an extended period of time, using opportunities to reiterate and reinforce principles, and asking students to engage with them through various activities. There is research that suggests that the representation of ideas in memory is a two stage process, where new learning is linked to existing memory through temporary connections that become replaced over time (e.g. days, weeks, months) by permanent neural connections - but only when the new material is actively reinforced (110). Otherwise, even if a student has a representation in the brain that could help them to recall the material, it is very unlikely to be activated due to the lack of connecting associations.

Simplistic notions that the teacher's aim is to substitute canonical concepts for alternative conceptions are then inconsistent with research into how thinking shifts. Once an idea has been adopted and applied, it will leave a trace in memory. A conception that has come to be been habitually applied (because it is commonly used in everyday life, or within formal learning without correction) is not actively deleted from memory, and only when it is not applied over a long period will its activation become less likely. The canonical conception is then in a sense competing for attention in what can be considered the learner's 'conceptual ecology' (111), and will only slowly tend to be preferentially brought to mind by the learner with extensive successful application.

That conceptual change of this kind is a complex process may be appreciated from historical examples. Priestley, for example, despite being an influential and skilled chemist, did not choose to abandon the phlogiston theory in the face of the alternative perspective offered by Lavoisier that has been characterised as the basis of the chemical revolution (112). Thagard has argued that although history may suggest Priestley was mistaken, his failure to shift to a new way of thinking was not irrational: rather that given his decades of experience of making sense of chemistry in terms of the phlogiston theory, it actually offered greater explanatory coherence for him than (his understanding of) Lavoisier's approach. It takes time to work with a new perspective and explore its affordances, and so give it the opportunity to prove to be more productive than better established ways of thinking.

Therefore, effective pedagogy requires two phases. Initially the teacher has to help students see that there are reasons to doubt the utility of their existing conceptions, and to appreciate the potential advantages of the canonical way of thinking. Then there need to be extensive opportunities for reinforcement over time that require learners to re-active the new learning and engage with it, so to trigger the brain's automatic consolidation processes.

The first phase may involve offering laboratory activities or teacher demonstrations where learners predict outcomes based on their conceptions, but find anomalous results that need to be explained (113). However, this may need careful structuring as students may readily perceive or interpret results according to their pre-existing expectations (114), potentially reinforcing their alternative conceptions. It is known that laboratory work is often 'hands-on' but not 'minds-on' (115), as often students working with new techniques and negotiating the practical requirements of activities (collecting equipment, setting up, observing and recording, coordinating with lab. partners, etc) may be working at full capacity, and not thinking deeply about the interpretation of what they are doing and seeing. Teachers needs to actively bring students' attention to teaching points that are meant to be demonstrated, but may not be spontaneously salient to learners. As one example, it is common in secondary education for students to prepare NaCl by neutralisation and evaporation of the resulting solution. If asked why there are ionic bonds in the product, students will commonly report that this is because in the reaction sodium atoms donated electrons to chlorine atoms: even though their reagents already contained solvated sodium ions ($NaOH_{(aq)}$) and chloride ions ($HCl_{(aq)}$). Students are often so confident in their existing thinking, that they do not notice it is inconsistent with other knowledge (if asked, they can report the species present in the reactants) and empirical evidence.

Channelling student thinking may involve thought experiments (116) that provoke *reductio ad absurdum*, or a series of bridging analogies (117) that start from a situation students already understand canonically, but which shift thorough a sequence of steps to show how the same principles apply more generally - including in those contexts where they tend to apply alternative conceptions. During the learning process students need to be able to compare their existing thinking with the canonical perspective, and find good reasons to consider the latter may be more productive (perhaps initially only in some situations where it can be demonstrated that existing conceptions do not work). Later the teacher needs to review and reiterate the new learning whenever teaching opportunities arise.

Mortimer and Scott argued that effective classroom teaching was akin to conducting a symphony orchestra, with shifts between movements where the class are focused on tasks that involved exploring and comparing available ways of thinking, and movements where the teacher orchestrated a public dialogue that explored the limits of students' alternative conceptions and introduced and championed the target knowledge (99). Such teaching needs to be designed, to adopt another simile, as if choreographing a ballet, by planning transitions back and forth between allowing students to work in groups on productive activities and then the teacher leading the class, first channeling dialogue about different ideas, and later offering the authoritative voice. Sometimes the group work may be laboratory based: but there are other activities which can be effective. As well as concept cartoons, and diagnostic questions, small group discussion can be based around interpreting some data in a table or graph (or arguing whether a trend can be extrapolated beyond the range provided), a narrative account of experimental work, or - as student conceptions often reflect historical but now discredited scientific thinking (118) - a suitably adapted version of a historical account (e.g. discussing phlogiston, caloric, the 'inert' gases, protons as fundamental particles). Such activities demonstrate that even famous chemists had ideas that would now be considered alternative, and that testing such ideas has contributed to the development of the subject. There is no reason why a similar approach cannot be used within university lectures, although the 'score' would have a different profile, with less frequent and briefer periods of focused group-work interspersed at critical points in lectures.

Some examples of potential activities might be:

- A teacher might ask students what can be predicted about the melting temperature of sodium chloride and the conductivity of its solution if the structure was based on ion-pairs which are weakly attracted to other ion-pairs, and are the main solvated species in solution (119). They can then be asked to access some comparative data for NaCl and simple molecular compounds.

- As students commonly explain the reaction $H_2 + F_2 \rightarrow 2HF$ in terms of the 'needs' of atoms (sic) of hydrogen and fluorine to fill their shells, a teacher might give half the class the task of explaining this reaction in small groups, and the other groups the task of explaining the reaction $2HF \rightarrow H_2 + F_2$, before then having groups share their responses (to appreciate the full shells notion has no explanatory value in understanding why reactions occur).

- An activity to challenge the idea that full shells or octets have a special stability might be to get students to plot the molar first ionisation energies across period 3, to give the familiar stepped figure. Students can then be asked to construct a trend line that adjusts elements 16-18 (S, Cl, Ar) for the effect of spin-pairing, and elements 13-18 (Al-Ar) for the effects of removing an electron from a p, rather than s, orbital. The actual graph gives a nearly linear plot (82), suggesting there is no particular extra effect due to Ar having an octet of electrons. As Ar has the highest ionisation energy, some students will need to be persuaded why the adjusted trend line suggests this is not an effect of the octet.In order to help make explicit for students how their existing thinking links to teaching, constructivist teaching schemes often start with elicitation of relevant knowledge (107). A technique that adopts this principle and can be readily applied in school and university teaching is known as P-O-E, which is an acronym for Predict-Observe-Explain (113). That is, students are first asked to make an explicit prediction, that is then checked, before being asked to explain their observations. This technique may be used in laboratory work, but can also be adopted in desk-based activities. As an example, consider a variation on the activity just outlined.

Students might be asked if they think there is a special stability associated with a full shell of octet of electrons, and if so how this might be found when measuring ionisation energies - say across period 2. This is complicated because the pattern of first ionisation enthalpies reflects not only a general trend across the period, but also differences due to the type of orbital (s, p) and the effect of spin-pairing. However, it is possible to seek to disentangle these effects, at least qualitatively. Students working in groups could predict how any special stability of an octet would show up in a plot showing the general trend of first ionisation energies across the period, and then be asked to use data book values to construct a graph that highlights this overall trend (e.g., see figure 1 for one approach). Seeing, and appreciating, the overall trend is important, because Ne clearly does have the highest first ionisation energy in the period, but the overall trend shows that there seems to be no substantial *additional* stability over the general pattern due to higher nuclear charge and smaller radii moving across the period. However, simply teaching this point may overload student's working memories (as well as being contrary to a tenacious alternative conception), where after engaging in the activity the teacher could then lead a class discussion to which students could meaningful contribute. There has been much discussion in educational scholarship on whether active (e.g. 'discovery') learning methods are more effective than direct instruction by the teacher (120). This is a false dichotomy - effective teaching often involves the expert carefully presenting a canonical account, but only once the students have engaged in appropriate experiences (in the laboratory, or otherwise) to fully appreciate the teaching.

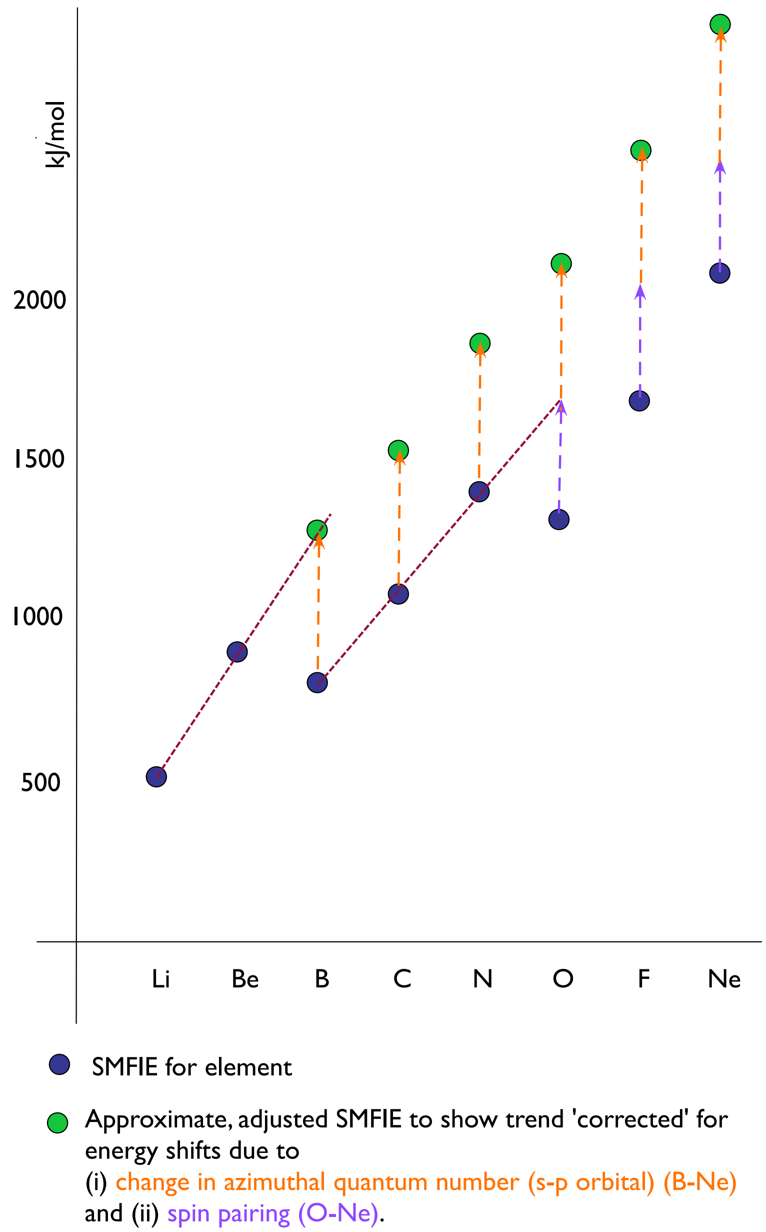

Figure 1: A construction to show the main overall trend of first ionisation enthalpy across period 2

Whilst an activity of this complexity is suitable for an examples class or tutorial, it does not fit so easily in a lecture. Yet the general approach of deferring 'telling' until after asking students to think and make a prediction, can easily be adopted in the lecture hall.

The teacher also needs to recognise that given the incremental and iterative nature of teaching, productive conceptual learning is often not a one-step transition, but may rather be a progression through a series of intermediate conceptions that each more closely resembles the canonical concept. This principle is often built into school learning in terms of a 'spiral curriculum' based around progressively more sophisticated understandings set as targets at different grade levels, and the development of various teaching models that offer 'intellectually honest' simplifications (121) of scientific models: that is pared-down accounts that are intended to be true to the gist of a scientific principles whilst leaving aside complexity that needs to be added later (122). University chemistry curricula may be designed to teach more fundamental ideas in the early phases, and leave more 'advanced' topics, that draw upon the fundamentals till later: but university teachers may wish to consider where they should go beyond this to teach more challenging concepts through a series of stages embracing increasing complexity (see §6.5).

6.3 Recruiting productive facets of student thinking

Although some especially well-established alternative conceptions may be tenacious, the recognition that many elicited conceptions may not be fixed features of a student's conceptual thinking, but the outcomes of making-sense in the context of a researcher's questions (see §4), cautions the teacher against treating all elicited conceptions inconsistent with canonical chemistry as targets for active challenge in the classroom. The perspective on learning developed in recent decades (see §3-5) suggests that formal concepts are built from the repertoire of interpretive resources a learner has available, including a good many intuitions about the world represented in implicit knowledge elements that are activated without conscious control. People develop their ontologies of the world based on their experiences (123), and commonly perceive simple linear causality even in complex interacting systems (so, for example, expecting viable reactions to go to completion), and construe processes (heat flow, chemical bonding) as substantive (caloric-like notions of heat, or the bond as an object in itself).

In the context of physics learning, diSessa identified a large number of such implicit elements (p-prims, see §4.1) and showed how they were recruited by students attempting to make sense of college physics. Each p-prim is an abstraction from some aspect of experience recruited by the cognitive system and used as a potential match to new experience. At a preconscious level the student notices that some phenomena appears to match some familiar pattern, and this is experienced as understanding. This may seem a trivial form of understanding, but arguably even the most theoretical arguments based on abstract concepts, are ultimately ground upon such intuitions. That is, any response to a 'why' question can be countered by 'and why is that?' until eventually the response is that this is just how nature is observed to be. A difference between expert and novice explanations is that the novice may react with 'that's natural, that's just how it is' very early in the explanatory chain (47). If a phenomenon is perceived in terms of such patterns then this satisfies the automatic need to make sense of the world. The scientific attitude, of course, is not be content with that, but to make explanations explicit, and test them logically, and explore how consistent they are with other aspects of our thinking: so part of the role of the teacher is to help learners put aside their implicit sense of whether they understand, and test out their thinking more formally.

As there are many different phenomena in the world, people abstract a wide range of patterns from experience, and so build-up a wide range of potential implicit modes for making sense. Often completely contrary explananda can make sense as a person has a diverse set of p-prims and so a different intuition can be applied in different cases. This may explain the phenomena sometimes found when students are asked to explain a range of different cases of the same type, and seem perfectly satisfied to offer very different explanations in different cases rather than seek one principle that fits all.

From this perspective, implicit knowledge elements, or spontaneous conceptions, are essential starting points for formal abstract concepts and the teacher's role is to help learners find suitable productive intuitions as a basis for developing canonical concepts. This approach has been explored in some depth in physics learning (65, 124-127), but less so in chemistry (128). However, there has been some limited research which suggests that students are indeed recruiting p-prim type intuitions when making sense of chemical phenomena (17): for example, a common pattern abstracted from experience is interactions where one active agent acts upon a passive 'patient' (129), and younger chemistry learners seem to apply this intuition when conceptualising reactions in terms of one active reagent forcing change upon another passive reactant. If they proceed with the study of chemistry they will meet such terms as oxidising 'agents' and nucleophilic 'attack' which fit the alternative conception that in a chemical reaction one reactant is active and the other is acted upon.

The general pedagogic strategy suggested here is to encourage learners to offer different ways of making sense of phenomena, and for them to spend time exploring the merits of the candidate ways of understanding - managed by the teacher who has sight of the target concepts. This therefore has much in common with the previous suggestions in that it requires students to actively explore ideas, and to engage in dialogue, so that different suggestions are championed and compared. This should be undertaken in the spirit of considering alternative conjectures, adopting the scientific values of open-mindedness, criticality, and avoidance of premature conclusions. The exploration and argumentation processes reflect the context of justification (130), that is seeking logical arguments for particular explanations. However, this can only proceed once some options have been suggested, which involves the 'context of discovery', which is equally important to science but, regrettably, seldom emphasised in science education (44). If students are not used to being asked to be imaginative in chemistry classes, it is possible to introduce techniques such as asking them to suggest analogies, metaphors, or similes (131), or asking them to build models or invent novel forms of representations (132).

The teacher, being the person with a clear view of the target knowledge, the canonical concepts, can also offer teaching models and analogies, and a range of supportive representations, that help channel students towards the desired conceptualisation. As suggested above, teaching is often misinterpreted, so it is important for the teacher to be explicit about the intended affordances (and the limitations) of such tools (133). As also pointed out above, students may lack epistemological sophistication, and the teacher should regularly reiterate the nature of models and other devices as imperfect and partial representations.

6.4 Explicitly teaching about models

There has been much attention in chemistry (and more widely science) education on the place of models in teaching and learning (134). At school level the curriculum often presents simplified models of scientific ideas as target knowledge, and teachers at all levels use modelling approaches in communicating their ideas - not just physical models, but gestures, cartoons, analogies, similes and metaphors (135-137). The subject matter of chemistry itself, is, as an empirical science, theoretical, and much that makes up the subject can be understood as being models. Indeed science can be understood as being centrally about building models of the natural world - both in terms of characterising what makes up the world, and producing explanations of what is observed. Models tend to simplify the complexity of what is modelled, and often involve the selection of specific features of interest. As the features of most interest may shift in different contexts, it is not unusual to shift between complementary models - so one model of a crystal structure may use small spheres linked by rods, and another model of the same structure may be composed of large spheres glued together. The question of which of these models is better, needs to be contextualised in terms of the particular aspect being considered at a particular time.

Even categories such as acid or oxidising agent or aromatic compound can be seen as simple forms of models (i.e., our typologies are models of perceived ontologies of the kinds of entities that exist in the world). The form of the periodic table is an attempt to best model the relationships it is intended to represent and explain - and thus there are alternative forms of 'the' periodic table which prioritise or exclude some features rather than others. Representations of the shapes of molecules can be understood as models. To the extent that something of the nature of a single molecule can sensibly be said to have a shape - the molecule does not have a distinct surface which acts as a boundary between itself and its surroundings - a molecule of methane is certainly not tetrahedral. The tetrahedron has distinct flat surfaces, clear edges, acute apices - and the molecule of methane has none of those attributes. (The modelling that leads to the tetrahedral assignment treats the hydrogen atomic centres as points and (ignoring the carbon atom!) imagines the solid object that would be defined by taking these points as apices - an abstract process of visualisation.) Reaction mechanisms are abstract models, as are reaction profiles. Ionisation energies are based on a model process (moving an electron to an infinite distance from the rest of an atom). There are many more examples: the subject matter of chemistry is largely a collection of a wide range of kinds of models.

Teaching explicitly about the status of ideas being presented (models, theories, etc.) may help learners appreciate the difference between teaching models and scientific models (so a physical model of the structure of a salt crystal may have physical links between spheres representing the ions, but only because this is needed for structure integrity of the model: bonds are not mechanical links); and between teaching tools such as everyday analogies (energy levels are like a ladder), mnemonics (e.g., OIL RIG to recall oxidation is loss of electrons, reduction is gain) and heuristics - used as memory aids or rules of thumb, but having no explanatory power - and more principled ideas.

So when the octet rule is taught it can be presented as a useful heuristic that indicates common valencies (88), so suggesting NH_3 is likely to be a viable compound, but NH_4 probably not as it does not follow the octet rule (although the ion NH_4^+ does), or that salts of calcium are likely to contain the Ca^{2+} ion rather than the Ca^+ ion. This helps novice learners check that species they are positing are likely to be chemically viable before they have sufficient experience of the disciplinary practice of working with the symbolic representations of submicroscopic species (138-140) to spontaneously recognise (intuit, see §3.5) likely errors they could make (e.g., MgCl, He_2, etc.). However, as a heuristic rather than a chemical law or principle, it should only be seen as a guide, and so then students will more readily accept exceptions such as B_2H_6 or SF_6. In particular, in this case, it is important for students not to see the octet rule as a chemical principe that acts as a criterion for stability as this supports decontextualised judgements such as considering Na will spontaneously emit an electron (as Na^+ 'is' more stable than Na) or that Na^{7-} will be a stable ion (22).

Many of the conceptual difficulties reported in student learning of chemistry can be understood in terms of the limited epistemological sophistication of the learners. In particular, students may not understand that (a) much of the scientific content is not intended as absolute descriptions of natural phenomena, but rather as scientific models; and (b) teachers quite sensibly often use teaching models that simplify the scientific accounts they are presenting as starting points for learning the ideas.

6.5 Teaching informed by the history and philosophy of chemistry

Teaching that makes the explicit nature of models a core emphasis from early in school science, and continuing through undergraduate study, might do a good deal to support learning of the diverse sets of ideas chemistry students are asked to engage with. One area of research in science education has focused on what might be considered students' epistemological commitments and thinking (141, 142): how they view the nature of scientific knowledge and how it is developed. This is related to a perspective on the teaching of sciences that argues teaching should be informed by studies in the history and philosophy of science (143-145).

Busy chemistry teachers, especially those already expected to teach courses outside their own areas of specialist knowledge, may feel that the need to keep up-to-date with chemistry content provides sufficient challenge, without delving into the much broader literature in what is sometimes called 'science studies'. Yet issues raised in this review suggest that wider perspectives may be valuable in developing ways to introduce material that supports learners. Some students may be mystified why a science such as chemistry teaches alternative, and apparently inconsistent, models in areas such as acids, or atomic structure. An approach to teaching these ideas that is informed by the historical context of their development may help learners appreciate the 'epistemic relevance' (146) of these abstract notions, by showing how they were creative responses to genuine challenges to making sense of nature that were met by chemists in their work.

This approach goes beyond simply teaching increasingly sophisticated models at different curriculum stages. For example, it may be that oxidation/reduction is met in terms of reactions involving oxygen and hydrogen, and some years later a (quite different) approach based on electron transfer is met. And then, later still, students are taught about oxidation states (an approach related to the electron transfer model, but abstracted beyond reactions that are actually conceptualised as involving electron transfer). The increase in sophistication could be seen as an employment of the spiral curriculum approach (see §6.2) where what Bruner called intellectually honest simplifications, pitched according to the age, developmental level, and prior learning of students, are used to teach abstract concepts. However, many students actually experience such approaches as being taught incorrect or inadequate material that they are later asked to discard in favour of new learning.

The approach recommended here goes beyond this in two ways: firstly, if the theoretical nature of knowledge, and in particular the value and role of models is emphasised (§6.4), then simpler models (of oxidation, acids, atomic structure, etc.) are not later seen as non-scientific simplifications to be abandoned later; secondly, if the step-ups in a spiral chemistry curriculum are introduced in terms of the limitations of previously taught ideas, and the empirical motivation to introduce a new model (that was once a pressing issue in the development of chemistry), then the connections within a sequence of models provide can continuity of learning for the students.

For those responsible for selecting curriculum material, such a historical perspective might also help determine which historical models still have a useful function in teaching and which might be redundant (147). Sometimes appreciating how current thinking has developed is valuable, however, as noted above (§4.3), sometimes current scientific presentations retain traces of now discarded thinking that has become 'fossilised' in how the concepts are discussed. That is, there are what the philosopher Bachelard called 'epistemological obstacles' (84), which act as distractions and are unhelpful to the learner. In terms of the previous paragraph, if "the limitations of previously taught ideas" are such as to make the ideas completely anachronistic then students should not be asked to learn them. There is an important distinction here then between (a) models which still have application, despite limited sophistication or range of application (worth teaching in their own right), and (b) those which are of purely historical interest (which may be worth engaging with to explain the development of current chemical theory, but should not be presented as target knowledge to be learnt and examined).

It has been noted that many alternative conceptions presented by learners reflect ideas that scientists working in the past themselves considered, or even adopted (118). The extent to which contemporary students' alternative conceptions can be equated with the theories of historical chemists, rather than just seen as having some superficial similarity, can be questioned - and likely in many cases students' alternative conceptions will not be carefully thought out or take full account of available evidence. Even so, such parallels offer teachers some insight into how their students could develop such ideas, and there may be value in pointing out such similarity to the students. That is, if a student offers a non-canonical idea, then they are getting the chemistry wrong, but if the teacher is able to point out that a historical figure of the status of, say, Priestley thought along similar lines (cf. §6.2), then this shows that there is no disgrace in entertaining such a way of thinking: the development of chemistry has depended upon chemists imagining, and then critically examining, a great many ideas that no longer have currency in the subject. It has been argued that teaching students via a treatment that acknowledges historical development of a topic can help avoid students developing alternative conceptions (148).

There is clearly some potential for ambiguity in the advice offered here. Teaching about the limitations of historical models may help students appreciate why chemists moved beyond them, and avoid students acquiring some alternative conceptions; and where we teach multiple models that may seen inconsistent, then a historical approach may help student see why less sophisticated models remain useful even if they do not suffice for all purposes. Conversely, given the challenges of learning our subject, we should look to avoid teaching approaches that present ideas with chemical currency in ways that retain vestiges of historical ideas that no longer contribute to current chemical practice, but are simply habitual ways of thinking and talking about the concepts. It is unreasonable to expect teachers to respond to these contrary imperatives without support from scholars with time to explore these issues in detail, and this is one area where curriculum development can be supported by more research into teaching and learning of chemistry topics informed by historical scholarship.

7. Summary and outlook

There has now been over three decades of research exploring student conceptions and related aspects of learning in chemistry. All chemistry teachers, at whatever level, should be aware that students tend to come to class with alternative conceptions which may influence how they understand and later recall teaching. It is generally agreed that teaching that ignores the phenomenon of alternative conceptions is likely to be less effective, whereas teaching that engages with student conceptions can make students aware of learning difficulties and help facilitate shifts towards more canonical understanding. Teaching that is dialogic in nature, that is, teaching that explicitly explores and compares alternative ways of thinking, supports desired conceptual learning (as well as arguably better reflecting the enquiry processes of science when compared to teaching that simply presents the scientific accounts as a *fait accompli*). Clearly such teaching is more demanding than presentations that simply offer the canonical accounts. In particular, it requires teachers to be aware of alternative conceptions that students at a specific level have in particular topics. This in turn requires teachers to engage with educational research, and - ideally - use forms of diagnostic assessment to guide their teaching.

Further research may help uncover conceptions in less well explored topics, or among groups of learners not well explored (in different cultural contexts and working in different languages), and can evaluate particular teaching approaches and tactics - the use of specific teaching models or analogies for example. As well as research into student conceptions of the chemistry, the research discussed here raises some related themes for further studies. One concerns the epistemological sophistication of learners: to what extent could more focus throughout chemistry education on the nature and roles of models and representations in science better equip learners to appreciate the limitations of (teaching and scientific) models and avoid the tendency to see these as realistic accounts? (149) A related issue concerns student metacognition (see §3.7) (150). Given how much of human cognition, including that at work during study, operates implicitly, it would seem that students who are able to recognise and interrogate the outcomes of intuitive elements in their thinking would be better placed to benefit from teaching. This could be highly significant in classroom and lecture hall contexts, where the teacher herself can only do so much to elicit and work with the alternative conceptions operating among a large class. More research on whether metacognitive training can support learning chemistry would seem indicated.

One theme in the present review has been the contrast between norms in school chemistry teaching and university chemistry teaching. In some part this may be justified given that university students are generally both self-selecting and selectively admitted, are more mature than school children, and have some years of formal chemistry studies behind them. However research shows that undergraduate, graduates, and chemistry teachers still often retain alternative conceptions. If effective learning requires exploration of ideas, dialogic methods, and active engagement in applying and testing concepts, then where university teaching is still based around lecture courses, the lectures need to have these features built in. Teaching that is a one-way presentation of information will inevitably often seem nonsensical or be open to misinterpretation given students' existing conceptions.

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