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Constructing active learning in chemistry: Concepts, cognition and conceptions

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Abstract

All meaningful learning is 'active' in the sense that the learner actively (although not necessarily consciously) links new learning with, and interprets teaching through, existing ways of making sense of the world. It follows then that conceptual learning in chemistry is iterative. Sound foundations in the subject support progression in understanding; but, equally, alternative conceptions (ideas at odds with the scientific models) support the misconception of teaching. Teaching can be misunderstood when the learner's existing understanding does not match the pre-requisite knowledge assumed in the teacher's presentation. A range of different categories of 'learning impediment' may result, when learners either fail to make the intended links with prior learning, or form idiosyncratic links with existing ideas that seem relevant from the student's perspective.

An engaging chemistry teacher, who provides students with a range of relevant learning activities, will inevitably produce active learning in the sense of the mental construction of new knowledge. The challenge here is to direct the learning processes towards ways of thinking which better match the scientific models prescribed in the curriculum. The research literature in chemical education reports a catalogue of alternative conceptions, derived where students have misconstrued chemical topics. Research is beginning to offer teachers a clearer understanding of the circumstances under which students are likely to misconceive teaching, and so how teachers can better channel the active learning of their students. This chapter offers an outline of constructivist thinking about learning, and presents a classification of the main types of learning impediments that misdirect learning. A number of examples are discussed. In particular the likely origin of the widespread 'octet' alternative conceptual framework - that many students adopt to explain chemical reactions, bonding and stability - is explored.

Key words:

constructivist model of learning; alternative conceptions/misconceptions; learning impediments; octet alternative conceptual framework; meaningful learning; misinterpreting teaching models; figurative language in learning

Active learning and chemistry education

This chapter explores the nature of active learning in chemistry in terms of how learners develop their conceptions of chemical concepts through cognition. The term '*active* chemistry learning' may suggest images of busy classrooms, with students moving about undertaking practical work, to find out the 'secrets of nature' for themselves. However, whilst such a classroom certainly can facilitate much chemical learning under certain conditions, it is not necessarily the case. Practical work, unless carefully set-up, can engage hands more than minds. Moreover, practical work that does engage minds is often unlikely to lead to the desired learning outcomes (Driver, 1983), unless it is very carefully structured and integrated within well-planned teaching sequences. So whilst physical activity is certainly a candidate for a feature of good chemistry teaching, it is not of itself a good sign of active learning. Rather, the focus needs to be on mental activity (Millar, 1989).

However, whilst ensuring students are mentally active and have their minds focused on the chemistry being taught in a lesson is likely to bring about learning, even this is not enough to ensure that student learning closely matches the intended learning. This can be appreciated by considering the large number of studies of student thinking in chemistry that have reported 'misconceptions' or 'alternative conceptions' (Kind, 2004; Taber, 2002). Research has elicited from chemistry learners a wide range of alternative conceptions (or misconceptions), which are inconsistent with the scientific concepts (Duit, 2007).

The 'constructivist' perspective, which has dominated thinking about science education internationally for some decades (Taber, 2009), interprets these alternative ideas as the outcomes of active learning processes; but active learning processes that led the student to a somewhat different understanding than that intended by the teacher. Constructivism has drawn upon psychological models of how conceptual learning is an iterative process, and has highlighted the nature of students' own conceptions in science topics. These 'alternative conceptions' (Gilbert &

Watts, 1983) reflect how each learner actively constructs their own knowledge, interpreting teaching in terms of their own existing understanding.

Constructivist premises

Constructivism has been informed both by philosophical arguments about the nature of knowledge, and by studies of learning from psychology and other cognitive sciences (Taber, 2009). Whilst there are many variations in the way constructivism is presented, it is based on some simple premises. In particular, human beings are inherently driven to make sense of the world. This is not something that depends upon a particular motivation, but rather it is hard-wired into our brains as part of our evolutionary heritage. We interpret flashes of light, and short extracts of overheard conversation, instinctively. We feel frustrated when we cannot understand something. We are by nature meaning-makers.

However, because much of this meaning making takes place at pre-conscious levels of cognitive processing, we are usually only aware of the *outcomes* of the process, not the process itself. We recognise a face, or a snippet of Vivaldi or the Beatles, without being aware how the actual sensations (of patterns of light; of vibrations in the air) became interpreted as something familiar. The same processes are at work when a student watches a chemistry teacher's demonstration or listens to her explanation for some chemical phenomenon. What is presented to consciousness is not raw data to be interpreted by the conscious mind, but the output of automatic processing that has often matched what is seen or heard to some familiar pattern represented at sub-conscious levels of the brain (Taber & García Franco, 2010).

Whilst is it possible to learn 'non-sense' information by rote, *meaningful* learning (Ausubel, 2000) requires the learner to associate what they see and hear with something they already 'know'. So the student makes sense of what they are taught in an internal as well as an external context. The external context is the classroom, in which the teacher talks and demonstrates, and students carry out various activities. This public context is shared by the teacher and all the students in the class. The internal context is highly personal: it is the mental environment in which new information is interpreted. This environment may be rich and multi-leveled: and as suggested above, includes stages of processing that occur before anything is presented to the conscious mind.

The term 'conceptual ecology' - drawing on Toulmin's (1972) notion of the evolution of concepts in an intellectual ecology - has been used to describe the context in which ideas are understood, and develop, in the human mind. The analogy here with how living things evolve in a particular habitat draws attention to the potential complexity of the mental system in which learning occurs (Taber, 2001b, 2009b). The conceptual ecology is not just the student's existing understanding of a topic, but also includes a range of *meta-conceptual* factors. As one example, explanatory coherence is something that is highly valued in science (Thagard, 1992): scientific explanations should be consistent across topics and even disciplines, and explanations that use already well-accepted principles are to be preferred to those that need to introduce new, additional premises. Any student who shares such values is primed with certain expectations of the scientific explanations met in class, and so is biased to interpret them in certain ways. Any student who has not adopted these values may not appreciate the unspoken assumptions of much teacher exposition, and so may miss much of the motivation for certain scientific ideas (Taber, 2008a).

Three broad classes of learning outcome

Learning is perhaps best understood as a change in the potential for behaviour: that is, learning has taken place if there is some change in the learner such that after learning they will behave differently in some possible situation than had been the case before learning (Taber, 2009). This is a general description, but commonly the type of behaviour we are most interested in is responses to questions and other such set tasks. If a learner undergoes some experience such that she is able to provide an answer to the question 'is carbon a metal' that was not part of her repertoire before, then she has learnt something. We need to note that such a general definition has implications: learning brings about a change in potential that may only be realised in specific situations; *and* learning that does take place in classrooms is not necessarily desirable from the educational perspective.

So for example let us consider a hypothetical student called Hilda. If she was asked the question 'is carbon a metal', she would answer 'no'. However, Hilda then attends a chemistry lesson on electrolysis, where she undertakes practical work using graphite rods as electrodes. Hilda has existing knowledge that graphite is a form of carbon, and that metals conduct electricity. During the lesson Hilda makes sense of the use of carbon electrodes in terms of her belief that metals (and only metals) act as conductors. Hilda comes to think of carbon as a conductor, and so a metal.

As a result of this learning experience, there are physical changes in the structure of Hilda's brain, such that the knowledge represented there is altered. We might say there have been changes in her 'cognitive structure'. If Hilda were now asked the question 'is carbon a metal', she would answer 'yes'. However, as Hilda is given no reason to demonstrate her new thinking in the lesson, the teacher does not detect this learning.

A week later, in a subsequent lesson, the chemistry teacher might ask the class if anyone remembers what material was used for the electrodes. Hilda is able to reply 'carbon, graphite'. Her active processing of the information that the electrodes were made of graphite, and her linking that into her knowledge about carbon, and about metals as conductors, supports her in remembering this as meaningful information (Taber, 2003b). The teacher is pleased with Hilda's learning. Although Hilda now thinks carbon is a metal, this is not elicited by the teacher's question, and a misconception remains unidentified. This is just a hypothetical case (some real examples are discussed later in the chapter), but illustrates both (a) how learning may be real, but not actively demonstrated unless elicited by a specific set of circumstances; and (b) how learning does not necessarily shift understanding in the intended direction.

If Hilda's teacher was committed to helping students form links between their scientific knowledge when opportunities arise, she might think to follow-up her question about the electrodes by asking something like 'why might we be surprised that we can use carbon as a component of an electrical circuit?', providing an opportunity to explore how carbon is generally considered a non-metal, but that the graphite allotrope has some properties that are unusual in this regard. We might even conjecture that despite (or perhaps because of) her earlier false assumptions, Hilda – a student actively looking to link her knowledge together - would be especially primed to learn from this aside. In this hypothetical case we might consider that Hilda held a particular epistemological commitment to the nature of scientific knowledge that was an active factor in her conceptual ecology (Hammer & Elby, 2003).

In principle, then, it is possible to identify three possible general classes of outcome when a student is exposed to teaching (see Table 1). One possibility is that no learning takes place. Whilst this is a theoretical possibility, it is seldom going to be the case in absolute terms. Any experience we have will activate some cognitive process (i.e. remind us of something) and is likely to forge some new links in cognitive structure (without necessarily being related to target knowledge: e.g. 'the colour of the teacher's tie is the same as the shirts worn by Manchester United footballers). Unless we are comatose, we cannot avoid some level of learning from our experiences. However, if a student can make little sense of a lesson, and has no motivation to pay attention, it is feasible that any learning related to chemistry will be fairly minimal, and we might for practical purposes consider there to have been no significant learning.

Level	Description	Notes
No learning	A student who pays no attention to a lesson may in principle undergo no learning.	In practice, we can learn incidentally even without consciously focusing on our surroundings. However such learning is unlikely to be effective in terms of academic progression.
Rote learning	Material may be learnt by repetition – e.g. mentally repeating it *verbatim* until it can be recalled.	Accessing such material in memory tends to rapidly become more difficult, unless there is medium and long-term reinforcement. Isolated material learnt this way tends to only be useful for low level tasks (i.e. being able to *recall* that Kekulé proposed structures for benzene; but not for explaining the significance of the structures he proposed).
Meaningful learning	Material that is actively processed by being explored in terms of existing thinking can be learnt meaningfully.	Meaningful learning is integrated into the learner's existing conceptual structure, which makes it easier to access later, and allows it to be used more flexibility in higher level tasks (such as forming and critiquing explanations). Meaningful learning can be just effective at representing incorrect understandings of chemistry as correct understandings.

Table 1: A caricature of three levels of learning from teaching

Rote learning

The second possibility is that some rote learning will take place (see Table 1). Rote learning concerns the learning of material that has no inherent meaning. An example might be a telephone number, where there is no automatic link between the pattern of numerals and the person who can be called on the number. Such information is not easy to learn, unless one spots some pattern to latch onto. For example, the number 191 41918 may be a burden to remember, but becomes easier to recall if recognised as the dates of the 'first world war'. Of course even a number which does *not* suggest such a pattern has been 'made-sense of' compared with the raw perceptual data (the sensory impression of the pattern made by ink on the page of the telephone directory): the numerals are themselves familiar, as is the process of constructing a telephone number from a string of numerals.

Interestingly, a good deal of early research into human memory was undertaken with this type of target – for example lists of nonsense letter triads to be recalled. Humans certainly can memorise such material, but it usually takes some effort. This is especially so if recall is required not later in the same test session, but some days, weeks or months later. Motivation is clearly important here. Learning something by rote usually requires time and effort that is unlikely to be invested without good reason. Indeed, the ability to effortlessly learn a large amount of such meaningless material is not only rare, but seems to be pathological (Luria, 1987).

This is highly relevant to education. If much course material has to be learnt by rote, then the students' task becomes both substantial and tedious. Meaningful learning is both easier and more interesting. It also offers flexibility in application as material learnt by rote can be regurgitated when, and only when, we recognise it is an appropriate response. However, not understanding the significance of learnt material means that it can only be presented 'as is', as so much mental ballast. Chemistry, as a science, is not primarily about isolated facts (the formula of ammonia, the electronic configuration of sodium, the molecular mass of sulphur dioxide – such facts are of little significance in isolation), but about *concepts that can be used to build extensive theoretical frameworks that offer explanatory value.*

Concept learning as meaningful

Concepts are inherently meaningful. A student may learn a concept label by rote, and even an associated definition, but if that is done without understanding then the student has not learnt the concept. There is certainly a good deal of rote learning in classrooms around the world, and sadly some approaches to chemistry teaching may indeed encourage such an approach. Yet students in such classes are learning facts, and NOT learning science. Although there is considerable discussion on how to best understand the nature of concepts (Gilbert & Watts, 1983), they may be most easily understood as categories. A student can be considered to have acquired a concept of 'metal', 'methane', 'molecule', 'metallic bond' or 'molecular formula' if they are able to make discriminations that allow them to decide when something is or is not a metal, some methane, a molecule, a metallic bond or a molecular formula. If they can make such discriminations, then they have a concept with that concept label: although this does not necessarily mean they make the same discriminations as the chemistry teacher would, and so have the 'same' concept. Hilda's concept of metal included carbon as an example, whereas her teacher's did not. Concepts tend to be understood in terms of the links they have with other concepts: metals *conduct electricity*, *copper* is a metal, metals have *metallic bonding*, metals are *ductile*, metals form *cations*, metals are a type of *material*, etc.

So the third main category of learning, then, is meaningful learning, where new information is understood in terms of existing conceptual frameworks, and new concepts are incorporated into those frameworks to extend them (see Table 1). This type of learning is educationally more valuable, offering flexible, applicable knowledge; is more interesting for the student; and involves the development of the type of knowledge that science itself seeks – knowledge that is coherent, integrated, systematic and so forth.

An irony, perhaps, in the context of a discussion of active learning, is that meaningful learning requires less effort than rote learning. Learning by rote requires deliberate focused acts of concentration. Meaningful learning just builds upon the brain's evolved ability to make sense of new information, which is automatic. Indeed a student who is intrinsically motivated by interest in a topic, and who is working at a level where new concepts are being met, or existing ones being developed, at a pace and level that matches their existing level of understandings, may approximate a mental state of 'flow' (Csikszentmihalyi, 1988) where sustained concentration seems effortless.

So the kind of active learning we should seek is not that where we encourage students to be active in terms of either physical manipulation or hard mental effort; but rather that where the match between current knowledge and new experiences allows engagement in the subject matter that best activates the natural cognitive processes associated with accessing existing knowledge, exploring how new material fits with old, and looking for new links and ways to incorporate new ideas into existing understanding.

Of course, student study experiences are seldom *explicitly* perceived this way – unless they are undertaking activities designed to make concept linking explicit, such as concept mapping (Taber, 1994). This type of mental activation can *sometimes* be achieved when a skilled teacher demonstrates and explains ideas to motivated students – although in general students taking notes from lectures will not fit the bill. Practical work can sometimes be effective, but not practical work for its own sake (Millar, 2004). Discussion tasks, where students have to explain and justify their reasoning in groups, can be very effective. For that matter, written exercises can sometimes support effective learning. In all these cases, the key is to structure the activity so that the student is thinking about the new in terms of their existing understanding, something that is only possible if there is good matching so that the new material does not seem trite, and is not pitched at a level too high for the students to make sense of it.

Indeed, the general principles here are no different in teaching chemistry than in effective teaching of history or geography or many other subjects. However, what chemical education research has revealed over recent decades is just how challenging the task of matching the new to the old is for chemistry teachers. In this regard, a key problem of chemistry education is NOT how to find ways of making learning meaningful for students, but rather *how to channel students towards the particular meanings the chemistry teacher is charged with teaching*.

When active learning goes wrong

Extensive research shows that whilst students do indeed commonly make sense of their chemistry lessons in terms of their existing understandings, it is often in ways rather different from that expected by their teachers (Kind, 2004; Taber, 2002).

One way of thinking about this is in terms of the teacher's role in bringing about learning. When the teacher presents a chemical topic, the learners will each interpret her words in term of their existing knowledge. Unfortunately, as learning is an iterative process, when students come to classes with alternative understandings of chemical phenomena, it is very likely that they will go on to further misinterpret the teacher's intended message. New alternative conceptions that the student finds useful for making sense of chemistry will be reinforced, and can in time be well integrated into the students' understanding of the subject. Such robust learning – whether matching scientific models or not - has potential to provide the foundations for further later learning (Taber, 2005).

The teacher then needs to present the material to be learnt in such a way that it can be understood as intended in terms of the learners' existing knowledge of the subject. The justification for studying learners' conceptions in chemical topics is that knowledge of how students understand chemical topics can inform teachers so that they can better support learners in acquiring scientifically acceptable models. As we have learnt more about the nature of learners' ideas it has become clearer that this is by no means a straightforward matter (Taber, 2009).

The chemistry teacher clearly expects and intends their teaching to be understood correctly, and so (whether through careful planning, or simply the implicit assumptions behind any attempt at communication) presents the information on the basis of a personal mental model of the learner's existing understanding. As an extreme example, a teacher taking an introductory chemistry class in a school is not going to base her explanations on explicit solutions of the Schrödinger equation, as she will know that the pupils will not be in a position to understand the chemistry in these terms. Whilst this is obvious, it is often much less clear exactly what level of prior understanding can be assumed when planning teaching. Certainly, an assumption that the class will understand correctly all the science that has been studied prior to the new lesson is likely to be rather optimistic given the catalogue of common alternative conceptions reported in the literature. For learning to be successful, there needs to be a good match between the presentation of material and the conceptual frameworks that pupils can call upon to interpret it, and that means a good match between the actual conceptual structures available to students, and the mental model of those structures used by the teacher to plan teaching.

Learning impediments

Learning can go wrong when there is a mismatch (Taber, 2001a). Such mismatches act as impediments to learning. Sometimes a student makes no sense of the teacher's presentation at all (either because the assumed prior knowledge is lacking, or because the student is not able to make the links the teacher intended). These situations have been referred to as 'null' learning impediments. We might imagine that our junior chemistry teacher using the Schrödinger equation would fall into the former category: a 'deficiency' learning impediment where the expected prior knowledge is lacking. An example of the second type of case, a 'fragmentation' learning impediment could come about when a teacher refers to the 'valence' shell of an atom, but the students have only previously heard this called the 'outer' shell. The students here do have the conceptual knowledge to understand the teacher, but due to the use of a different label do not make the intended links with prior knowledge.

Many cases of learning going wrong in chemistry, however, involve the learner actively making a link with existing knowledge, but an inappropriate one. These 'substantive' learning impediments are again of different kinds. In particular they may either derive from making links with existing alternative conceptions ('grounded' learning impediments), or by making inappropriate links with knowledge that is not relevant ('associative' learning impediments). An example of an inappropriate association would be that of a student inferring that the neutralisation process *necessarily* leads to a neutral product (Schmidt, 1991). Although the teacher does not make such a statement, the human brain seeks links and connections, and adopts a linguistic clue from the word 'neutralisation'. Here the active nature of learning is unhelpful from a chemical perspective.

I have found that some students who study biology and chemistry come to understand the term 'hydrogen bond' as meaning a covalent bond to hydrogen. What seems to happen here is that students learn from school chemistry that there are two types of bonds, ionic and covalent, according to the classification rules given in Table 2.

Type of bond	Found in
Covalent	Compounds formed between non-metallic elements
Ionic	Compounds formed between a metallic element and a non-metallic element or elements

Table 2: A simple typology of bonds in compounds

Later on in their chemical education they will be taught about metallic bonding, intermolecular bonding, polar bonding and so forth: but the most elementary courses often limit consideration of bonding to the two types shown in Table 2.

However, when they start advanced biology classes, students often find teachers referring to hydrogen bonds (which are obviously important in such contexts as proteins and nucleic acids), even though this concept has not yet been taught in their chemistry classes. Rather than realise this is a new class of bond, students may simply assume that these bonds between hydrogen and other non-metals are covalent bonds. So when the teacher uses the term 'hydrogen bond' it is understood to mean a covalent bond to a hydrogen atom. The student misunderstands, but having made a connection that allows the teaching to make sense in terms of prior learning, the student does not realise that they are misunderstanding.

Other associative learning impediments may be based upon drawing inappropriate analogies (something that has been labelled a 'creative' learning impediment). As one example, 17-year old Alice (a real case, but an assumed name) explained that a balloon that had been rubbed on a jumper would stick to a wall because of a 'relative' difference in charge: although the wall was neutral, this made its charged *relative to* the charged balloon, so they would attract. This seemed to be an argument by analogy with potential difference: an object at zero potential can be a source or sink for charge compared with an object at some other potential, as there is a potential difference. In making this creative link between how to conceptualise charge and potential, Alice missed another potential link that might have helped her. Alice knew that polar molecules can induce dipoles in other molecules leading to intermolecular attraction, but she did not think this might be relevant to the question of why a charged balloon would stay attached to a neutral wall (Taber, 2008a).

A related category of problem concerns what has been labelled 'epistemological' learning impediments, where the student fails to appreciate the role and nature of models and such devices as metaphors when they are used in science teaching. Models have limited ranges of application, but may well appear to students to be intended as accounts of how things actually are. Metaphors are only intended to give a flavour of how things are – but can be taken literally. A classic example of this is the delay before chemists managed to form compounds of the inert gases. The description of these elements as 'noble' came to be taken as an absolute description, so that few chemists would have thought of trying to react them with other substances. It is not just students who may find that the brain's tendency for active meaning making sometimes leads us astray.

Grounded learning impediments

So students may fail to learn because of lacking prior knowledge, or because they do not spot the intended connections; and they may learn something other than what was intended because they make unexpected and unintended connections. The other category of problem suggested above was grounded learning impediments. Here the student does recognise the area of prior knowledge relevant to teaching (the general area of prior learning targeted by the teacher), and makes appropriate links, but with existing conceptions that are already at odds with scientific models.

This immediately raises an important question: how do students come to already have alternative conceptions about chemistry, such that these types of situations can arise. This is particularly the case when we acknowledge that many of these alternative conceptions concern chemical concepts that are themselves abstract, and relate to theoretical entities such as molecules and bonds, and the like, that are by-and-large only met by pupils in the context of chemistry classes.

The model of different types of learning impediments I am drawing upon here (Taber, 2009) suggests three types of origins of student ideas which may be important when students develop grounded learning impediments about science topics. These are 'intuitive', 'life-world' and 'pedagogical' learning impediments.

The term intuitive learning impediment refers to those alternative conceptions that pupils appear to develop from their direct experience of the world (rather than being mediated through language for example). In physics education it has been found that a majority of students in most classes have, before receiving physics instruction, developed an intuitive understanding of the relationship between force and motion which somewhat reflects the historical 'impetus' theory (Gilbert & Zylbersztajn, 1985). That is, to make something move you give it a push, and as that push gets 'used-up' the object comes to a stop. Now that is not compatible with the account of force and motion presented in school physics, but it *does* describe our everyday experience of moving objects around. It is not too difficult to understand how most children acquire an intuitive feel for everyday dynamics (Georgiou, 2005), and indeed it took Newton to appreciate and codify the modern scientific understanding.

That can explain children's conceptions of dynamics, but it is not immediately obvious such an explanation can have much relevance to many alternative conceptions in chemistry. For example most students asked to compare the three chemical species Na^+, $Na^\bullet$, and Na^{7-} thought that the neutral atom would be a less stable species than the seven-minus sodium anion. This would seem an obscure deduction for most chemists or chemistry teachers. Students should know that metals form cations; that sodium has a valency of one; that highly charged ions are difficult to stabilise and so rare. Sodium compounds met in school and college chemistry inevitably only involve one sodium species, the Na^+ ion. Whilst the neutral sodium atom is readily ionised, it has no tendency to attract electrons. Yet in a series of small-scale studies, involving 16-18 year-old UK students studying chemistry in a range of schools and colleges, it was found that clear majorities of each sample thought the anion would be more stable than the atom (see Table 3).

Study	N	Students judging Na atom less stable than Na^{7-} anion
Taber, 2000	29	72%
Taber, 2009a – study 1	19	89%
Taber, 2009a – study 3	33	64%

Table 3: Student judgements about the stability of the hypothetical Na^{7-} ion

A second source of alternative conceptions has been labelled ‘life-world learning impediments’ as they relate to what is taken as commonly accepted knowledge in the ‘life-world’ of everyday discourse (Jegede & Aikenhead, 1999) - the way ideas get communicated through culture, whether they are scientifically valid or not (Solomon, 1987). So in everyday discourse it is common to think that pure substances are safe, chemicals and radiation are dangerous, that acids burn through objects, and so on. Most of these ideas need some *realignment* to fit with the canonical chemical understandings. It would actually be more appropriate to say that these ideas need *translating*. For it might better to understand such terms as homonyms for chemical terms. ‘Acid’ in the life-world is the label for a different, if overlapping, concept to ‘acid’ in chemistry. In everyday discourse freshly squeezed orange juice is considered pure because it does not contain any chemicals, especially nasty ones like acids. To the chemist, the orange juice is not pure, contains acids, and must by definition be comprised of chemical substances. It is understandable that such different usages and meanings cause problems when students cross the cultural border from the life-world to the discourse of the chemistry classroom (Aikenhead, 1996).

However, whilst this explains some learning difficulties in chemistry, it again does not seem to offer a viable explanation for many of the reported alternative conceptions that relate to the submicroscopic world of atoms and molecules (Harrison & Treagust, 2002). Consider, for example, how students commonly respond to being asked why hydrogen, H_2, reacts with fluorine, F_2. Chemists may think here in terms of thermodynamic considerations. Yet when students who studied this topic at senior high school/college level were asked this question the most common response was that the reaction occurred so that the hydrogen and fluorine atoms could full their outer electron shells (Taber, 2002).

Now the most bizarre thing about this response is that it does not make any sense in its own terms: the atoms concerned already have full shells in the reactants! Yet most of the students were so convinced that reactions occur to allow atoms to complete their electron shells and/or gain ‘octets’ of electrons, that they did not notice they were offering an answer that was inconsistent with the information given in the question. This raises the question of why students could become so committed to the abstract and unscientific notion that the driving force for chemical change is the need of atoms to complete electron shells. We might explain why school pupils assume gases have no weight in terms of the intuitive learning about the world; and why they may think all polymers are ‘plastics’ in terms of life-world discourse; but developing an explanatory principle based on electron configurations is hardly the stuff of common experience or popular conversations.

Pedagogic learning impediments

This leads to the final category of grounded learning impediment that can lead to alternative conceptions about chemistry: what pupils have previously been taught. That students commonly form alternative conceptions about the nature of the theoretical submicroscopic entities used as the basis for so many explanations in chemistry – entities such as ions and molecules that they have never directly experienced, and which are seldom the subject of everyday discussion outside of the science classroom – points to teachers ourselves being culpable in misleading students.

So sometimes, and perhaps more often than we might wish to acknowledge, students come to classes with existing prior knowledge that is inconsistent with the chemistry they have to learn, and yet derives directly from what they have been taught previously.

Sometimes this is due to limitations in teacher subject knowledge. The experienced chemistry teacher who told me that strong acids *always* have a pH of 1 simply did not understand (or had been teaching at a basic level for so long that he had forgotten) the scientific principles involved. School level textbooks that state unequivocally that the third atomic electron shell is filled with eight electrons would seem to reflect limitations of the authors' own subject knowledge. In both of these cases the statement is wrong, but is unproblematic in the context of the level of teaching being undertaken. However, in both cases, if students learn these 'facts' and then opt to study chemistry at higher levels, they will find that their prior learning interferes with their understanding of later teaching.

Such pedagogic learning impediments are unfortunate, and would not happen if teachers (and text book authors) had perfect subject knowledge. Yet we are all fallible, and most teachers are likely to have subject knowledge with some flaws (Goodwin, 2002).

The Octet alternative conceptual framework

However, this cannot be the whole picture. Students do not only acquire isolated alternative conceptions, but extensive conceptual frameworks based around dubious learning. Indeed a number of the examples I have used in this chapter relate to an alternative conceptual framework based around the central idea that chemistry occurs to allow atoms to obtain full shells or octets (Taber, 1998). This is clearly the basis for students' explanations of why hydrogen and fluorine react. It is the starting point for students claiming that Na^{7-} will be stable, along with a range of other chemically dubious species (Be^{6-}, C^{4+}, C^{4-}, Cl^{11-}).

Yet it seems unlikely that teachers deliberately teach that the reason chemical reactions occur is to allow atoms to fill their electron shells. Perhaps some do, but it seems more likely that the situation is more complex that this. Usually students will have studied several years of basic chemistry before they meet chemical explanations for why reactions occur. Initially students may not think about why with some combinations of substances reactions occur, but not others. Rather, they will tend to simply make sense of chemical reactions in terms of intuitive knowledge elements that are no more than generalised patterns abstracted from experience: e.g. 'it is just natural for chemicals to react when mixed'; the 'stronger chemical forces the weaker one to react' (Taber & García Franco, 2010).

However the 'explanatory vacuum' created by ignoring the driving force for chemical reactions in elementary classes comes to be filled by students' interpretations of what they are taught about the submicroscopic world. Bonding is often presented in terms of the 'needs' of atoms to fill their shells. Strictly arguments about electronic configuration should only be used to explain valency, not the existence of bonds *per se*. However, the impression often given is that bonding occurs because atoms 'want' to gain full shells. Isolated atoms are seldom important in real chemical processes, but they provide a convenient place to start explaining chemistry, and students readily acquire notions of the atom as the starting point for all chemical processes (Taber, 2003a). So when students learn about the two basic classes of bonding found in compounds (Table 2), they are often taught that covalent bonding is 'sharing' of electrons (which allows atoms to have full shells) and that the ionic bond can be understood in terms of electron transfer between isolated atoms. That is they see a hypothetical and often irrelevant electron transfer – which allows atoms to have full shells - as the basis of, or even as, the ionic bond.

It is worth considering the status of the information in Table 2, i.e. does this represent sound chemical knowledge? Clearly Table 2 makes no reference to bonding in metals as it only concerns compounds, and it ignores intermolecular bonding. It also includes unrealistic ideal cases. Bonds in compounds can seldom be considered as pure covalent, and never purely ionic. In a sense then, Table 2 is not scientifically accurate.

However, Table 2 presents a level of knowledge often considered suitable for basic level chemistry learning. The most sophisticated scientific knowledge available is seldom suitable as target knowledge in the school curriculum. Rather there is a process of reconceptualising scientific knowledge into something more suitable for the learners (Gilbert, Osborne, & Fensham, 1982; Taber, 2008b).

Table 2 present a model of bonding in compounds suitable for introductory learning. If the model in Table 2 is taught and learnt as if absolute, factual knowledge then it is inaccurate. If, however, it were to be taught and learnt as a useful model that can often be applied, then it is no longer problematic. After all, this simple classification is often good enough for many purposes in chemistry, and is used by professional chemists all the time.

However, for students, bonding is about atoms filling their shells, and the ionic and covalent models are closely linked to achieving this. This makes sense of why students commonly see ionic substances such as NaCl as pseudo-molecular (Butts & Smith, 1987; Taber, 1994a). The ionic bond, students deduce, is between specific pairs of ions that have a shared history of having been involved in an electron transfer event. It follows from this way of thinking that the ions in NaCl can only form one bond, as the atoms only had one electron to donate or accept in achieving full outer shells. This also suggests that when NaCl dissolves, these strongly bonded ion pairs will enter solution, having only been attached to other ion pairs by 'just forces', not actual chemical bonds.

This model of ionic bonding does not explain the properties of hard crystalline NaCl which dissolves to form electrolyte solutions, and when students make NaCl by neutralising acid and alkali, and evaporating the water, there are no electron transfer events involved. However, despite the limitations of this way of thinking, it offers an enticing coherent story of chemistry being about atoms needing to fill their shells that seems to be accepted by many students. The brain's tendency to actively seek meanings and patterns latches onto a principle (the desirability of full shells) that can be widely interpreted to make sense of a good deal of chemistry at the submicroscopic level.

Unfortunately this way of understanding chemistry provides a major learning impediment in more advanced studies. As bonds are not seen as physical interactions between chemical species, students find it difficult to accept that intermolecular interactions can be considered as bonds (as they do not help atoms full their shells); do not appreciate that there can be bonds 'in-between' ionic and covalent; have difficult understanding compounds such as CO, $AlCl_3$, or SF_6 that do not have atoms with 'full shells', and they readily revert to explaining chemical reactions in terms of the need of atoms to fill their shells, even after being taught canonical chemical explanations (Taber, 2001b).

Chemical concepts, chemical learning, and correcting conceptions

To some extent the alternative 'octet' conceptual framework can be considered a *pedagogical* learning impediment. It is an aspect of prior learning, based on school chemistry teaching, which blocks later effective learning of chemistry. Yet that is a simplification, for few chemistry teachers are intentionally teaching this framework. Rather the combination of the abstract and inaccessible nature of the concepts (atoms, bonds, etc); the delaying of teaching any canonical basis for chemical reactions; the general intuitions about the world that students bring to lessons; the limited epistemological sophistication of learners; and the particular simplifications teachers use in basic chemistry courses, conspire to lead many students to develop the alternative conceptual framework.

The 'explanatory vacuum' provides a niche into which the active learner (automatically seeking connections with prior understanding) interprets what she sees and hears. So she makes sense of the teaching models presented as best she can.

The limitations of models and metaphors

The simple bonding typology represented in Table 2 is a teaching model; a simplification that is useful provided it is understood as a model with a limited range of application. That may seem obvious to the teacher – after all, most of what we teach in chemistry can be understood as models in this way. Yet pupils lack the sophistication to appreciate this until we teach them about the nature and role of scientific models. If the teacher does not make the status as model explicit when presenting the bonding typology, then students learn it as a fact, and continue to see bonding as a dichotomy even when taught about polar bonds (e.g. seeing them as no more than a variation on covalent bonding, rather than the most common class of bonds). In terms of a typology of learning impediments, we might better class this as an associative (epistemological) learning impediment, rather than a grounded (pedagogical) one (see Table 4).

The topology presented in Table 4, like the one in Table 2, is a model. The typology is intended to help teachers think about where learning can go wrong, but like all models it has limitations. Probably, in most cases, the octet framework is something of a hybrid of 'epistemological' and 'pedagogic' learning impediments, with traces of some other categories present as well.

Main category	Nature	Sub-categories
Grounded learning impediments	Occur because existing understanding is inconsistent with accepted scientific thinking. Such 'alternative conceptions' may derive from various sources:	• 'intuitive': …the students' own intuitive interpretation of the way the world seems to be; • 'life-world': folk beliefs - common scientifically dubious ideas acquired from friends, family, the media etc; • 'pedagogic': impediments due to limitations of previous teaching, such as over-simplification, use of poor analogies and unhelpful models, etc.
Associative learning impediment	Occur because the student makes an unintended link with prior learning. These may be of various types:	• 'linguistic': - taking a cue from a word's 'everyday' usage, or the similarity of a word with the label for an existing concept; • 'creative': inappropriate analogies - spotting (creating) an unhelpful analogy between the material being taught and some existing knowledge; • 'epistemological': over-interpreting models - or lacking the epistemological sophistication to appreciate the limitations of models, analogies and metaphors used in science teaching, and so interpreting teaching in a too literal and absolute sense.

Table 4: How active learning can go wrong: types of substantive learning impediment – after (Taber, 2009).

The failure to appreciate the nature of models can be very frustrating for students – so when faced with learning an orbital based model of the atom, some students feel that earlier teaching about electron shells was little more than lies. The loose anthropomorphic metaphors that chemistry teachers commonly use in their classes - 'carbon wants to form four bonds', 'metals like to form cations', 'the chlorine atom needs to fill its electron shell' - are not literally true: they are shorthand ways of talking about low energy configurations, and charge interactions, and so forth. But when such language is habitually used, it is little surprise that students who have not yet met the scientific explanations, come to adopt these metaphors as scientific principles (Taber & Watts, 1996). The notion of atoms with full shells having a particular special status also seems to appeal intuitively: being whole and complete and symmetrical perhaps suggests desirable, and strong, and stable.

Conclusion

This chapter has explored the notion of active learning in chemistry in terms of cognition, the mental activity that leads to the development of conceptual understanding. In general we want learning to be 'active' in this sense. Active learning is more interesting, easier, and leads to knowledge that is more readily recalled, better integrated, and more flexibly applied. All of this is to be welcomed.

However, the activity of the brain leads to each student interpreting teaching in a unique way in terms of their existing knowledge, and various nuances of how they understand particular terms and whether they appreciate the nature of the models and metaphors teachers use to communicate abstract and difficult ideas. A key message of this chapter is that active learning can easily go wrong. However the alternative – learning by rote so that what is recalled is an empty facsimile of what was taught – is not a useful one if we are trying to teach a science rather than a chemical catechism.

In some ways this chapter may seem very negative, as it illustrates how a whole range of types of learning impediment can stand in the way of chemistry teachers communicating scientific ideas to learners. However, this could also be seen as demonstrating just what an achievement it is when students do learn the scientific models and become good chemists.

The main message of the chapter is intended to be neither despondent nor celebratory, but rather to be guardedly optimistic. There are considerable challenges in teaching the abstract concepts of chemistry, and much potential for the active learner to misinterpret teaching. Yet the examples discussed here show that we are beginning to move beyond research that reports students' alternative conceptions, to understand what is going on when students develop their alternative understandings, the intuitions they bring to class, and the ways they tend to interpret our teaching models. That is surely an important step towards designing chemical instruction that can draw upon the brain's inherent tendency to meaningful, active learning, rather than so often being thwarted by it.

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