

Misconceiving chemistry: the mismatch between chemical concepts and student thinking

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ABSTRACT Many learners seem to find chemistry a very difficult subject and it is common for them to form misconceptions. This is not so surprising in view of the diverse range of abstract theoretical models taught in chemistry classes. Research into learners' chemical thinking offers insights that can help teachers think about how best to present chemical concepts. Students hope that chemistry will be exciting but the complexity of trying to understand explanations, and the frequent revision of those explanations, can be confusing and disheartening. This can compromise understanding and motivation to progress to further study and chemistry-related employment.

Chemistry is a school subject that divides students: some love it and others find it exceptionally difficult. Indeed, there are often two very different types of chemistry lesson. Some involve bangs and smells, pouring coloured liquids and collecting gases, and the use of test tubes, acids and Bunsen burners. Then there are the lessons spent doing mole calculations, balancing equations, learning atomic and molecular structures or considering how ammonia is made on an industrial scale. This is of course a simplification, but it has a considerable grain of truth. For many secondary-age students the first type of chemistry lesson is fun; the second type is confusing and – even – boring. Moreover, and this is often the crux of the issue, for many secondary students there is limited connection between the fun chemistry and the boring chemistry. This is because so many students find basic chemical concepts abstract, counter-intuitive and difficult to relate to anything they find meaningful. The challenge of chemistry teaching is to show learners how the abstract principles, theories and models relate to, and help explain, the chemical phenomena – the bangs and colour changes, etc. – that most students find intrinsically fascinating and exciting. For those who 'get' these connections, chemistry is a wonderful subject. For the rest, chemistry can lose popularity as the ratio of theory to practical work increases. Teachers

working in the UK now have to consider how best to make such connections in the context of teaching that emphasises 'How science works' and seeks to produce scientifically literate citizens.

There are of course some students who find the theoretical aspects fascinating, and see as much wonder in the chemical concepts as in the bench phenomena. These students are important; they are amongst those most likely to become the future chemistry undergraduates, professional chemists and chemistry teachers. However, they are, sadly, the minority in most school classes.

This article explores the challenge facing chemistry teachers in terms of what we now know about learning in chemistry and the nature of pupil thinking in the subject. The challenge is significant, but our developing understanding of the nature of the problem can offer guidance to teachers, those responsible for developing chemistry courses and those preparing the next generation of teachers.

The nature of chemistry as a science and as a school subject

Chemistry is often said to be a practical subject, and that is certainly the case. Chemistry is about substances and their properties, and in particular their behaviour when mixed with other substances. To study the subject without working in a laboratory investigating and demonstrating

the properties of a range of substances would be facile, and hardly fits most chemistry teachers' idea of what learning their subject should be like (even if this is necessarily the experience of students in some educational contexts where resources are limited or practical experiences are not the norm).

However, when we say that '*chemistry is a practical subject ...*', we take it for granted that we imply '*... as well as a theoretical subject*'. Chemistry is above all a science, and science is concerned with the development of systems of theoretical knowledge that reflect, summarise, explain, organise and interrelate, and are justified by, empirical observations.

To emphasise the empirical aspects of chemistry to the exclusion of the theoretical aspects, or vice versa, would distort chemistry as a science. This is particularly clear in what we might call the 'post-positivist' period. At one time it was argued that science could be built on sure foundations, so that it offered absolutely reliable knowledge. However, during the twentieth century, debates about how science provides knowledge made it clear that all human knowledge, even in science, has to be seen as ultimately 'provisional', in the sense of being open to question in the light of new information. Moreover, whilst there are still very good grounds for believing that science can offer reliable (if not absolutely certain) knowledge, it also became clear that science depends on the intimate relationship between ideas and evidence: data are meaningless without human interpretation, but good ideas can only develop into scientific theories when well supported by carefully collected, analysed and critiqued evidence.

We should then think of chemistry, like any science, as neither a practical nor a theoretical subject, but rather as subject built on the interplay of empirical observations and conceptual notions.

We should be careful, however, not to assume that *school chemistry* will automatically reflect this. School subjects are constructed by curriculum authorities influenced by a wide range of interest groups, and will only reflect an academic discipline to a limited degree (Kind and Taber, 2005). This should be very clear in the case of chemistry, which at the end of the 1980s ceased to be an official subject in England during the years of compulsory schooling. At this point 'science' became the subject referred to in

all curriculum documents, and the subject that chemistry graduates entering teaching *had to be prepared to teach*. (The ambiguity of this phrase is deliberate: universities had to prepare graduates to teach across the sciences, and – if they wanted to work as school chemistry teachers – the graduates had to accept that.) Despite the more recent support from UK prime-ministerial level for more students to study separate sciences at upper secondary level, the recent revisions of the English National Curriculum still avoid using the term 'chemistry'.

The important point is that school chemistry *cannot* be the same as real chemistry, and in some respects this is just as well. The cost and health and safety aspects of students being allowed to do exactly what research chemists or industrial chemists do on a daily basis, even if this was judged desirable, would clearly be prohibitive. The challenge then is ensure that school chemistry is *both* suitable for students *and* a sufficient reflection of the practice of chemistry itself – so that it offers students an authentic flavour of the discipline. As one key criterion, authentic chemistry education would reflect the strong interplay between ideas and evidence that is at the heart of the sciences (Taber, 2006). Authentic chemical education must introduce sufficient concepts and offer sufficient theoretical content for students to appreciate how that interplay is part of the very essence of chemistry.

This requirement is at the crux of the problem of offering chemistry education that will appeal to youngsters, for it is well established that the conceptual aspects of school chemistry are very challenging for most students. Yet reducing the conceptual content leaves something that is no longer authentic science and is less likely to appeal to the very students who are potentially the chemists of the future.

Students' ideas in chemistry

Over the last 30 years there has been a good deal of research exploring student thinking in scientific topics (Duit, 2007). Much of this work has been undertaken from a 'constructivist' perspective, which recognises that knowledge is built up in each individual student's mind, and cannot be transferred wholesale from teacher to student (Taber, 2009a). This perspective emphasises the important role of current knowledge and understanding in interpreting what we see, read

and hear, and in forming new knowledge. Quite rightly, it was recognised that teachers need to understand what their students currently think, if they are to plan effective teaching that will not either ‘go over their heads’ (if it does not seem to link to anything students can make sense of) or become significantly distorted (as the learner misinterprets the teacher’s intended meaning).

Much research has therefore been undertaken to characterise learners’ ideas and many examples have been identified of where students (either before or after teaching) have ideas at odds with school chemistry. These examples are often collectively labelled as ‘misconceptions’, although this may obscure important differences among ideas that may be better categorised with such labels as implicit (intuitive) thinking, alternative conceptions and conceptual frameworks (Taber, 2009a).

Examples of chemical misconceptions

There are too many reported misconceptions to catalogue in a single journal article. However, some of those found in the most fundamental chemistry topics have been discussed in materials the Royal Society of Chemistry (RSC) has provided to UK and Irish secondary schools and colleges (Taber, 2002), and Vanessa Kind has provided a review of major topics (Kind, 2004) that can be freely downloaded from the RSC website.

However, consider the following examples:

- 1 The product of any neutralisation reaction is neutral.
- 2 A reaction occurs whenever two substances are mixed.
- 3 The + symbol in Na^+ implies an atom with one electron in its outer shell.
- 4 In a sodium chloride lattice, each sodium ion is bonded to the one chloride ion it donated its extra electron to.
- 5 The Na^{7-} ion will be more stable than the Na atom.

These are just some of the many examples that could have been selected, but these will suffice to show that:

- such misconceptions apply across a wide range of topics, and educational levels;
- there can be a range of different misconceptions about a single topic (e.g. sodium ions in examples 3–5);
- some ideas held by students may seem quite bizarre to their teachers and unlikely to be

expected unless one has taken time to explore what students are thinking (e.g. the last example);

- simply labelling such ideas as ‘misconceptions’ may ignore some quite important differences in how and when these ideas appear, and how we might best respond to them.

Before demonstrating these features of students’ ideas, it is useful to consider something of the nature of the chemical concepts that we ask students to learn.

The challenge of learning chemical concepts

As teachers, it can sometimes be difficult for us to recognise why concepts that we have been working with for years, if not decades, seem so problematic for many of our students. The teacher needs to be able to perceive the subject material ‘at the learner’s resolution’ to recognise why what seems obvious to the expert may not be so readily apparent to the novice (Taber, 2002).

In particular, we need to recognise that education tends both to reverse some of the logic of a science discipline, and to constrict the development of understanding rather severely. Chemical concepts are human constructions that have been developed over centuries and we expect students to learn them over a few years. These constructions were developed to deal with situations and problems that arose in the context of chemical research. In the classroom we present these solutions to learners who never had the problems they were created to solve, and then offer some examples to demonstrate the ‘solution’. We are seldom able to recreate the original problem situation to enable students to see what motivated the development of the new concept.

When I say that chemical concepts are ‘constructed’, I am aware that there is a danger of being associated with some extreme views that may seem inappropriate. Those working in science education who claim to be ‘constructivists’ are sometimes accused of being ‘relativists’. Genuine relativists believe that scientific ideas do not offer objective knowledge of the world, and are little more than a kind of intellectual fashion. Such a view would suggest that chemistry today is not an improvement on that of Dalton, or indeed the Alchemists, but ‘just different’ – because the way we look at and understand the world is determined by various cultural factors. An extension of this

idea is to consider that students' own ideas should be treated as just as valid as those in the science curriculum, or those reported in the latest top science journals.

That is not what most constructivists are suggesting, as there are very good reasons for thinking chemistry has progressed since Dalton, and for expecting chemists' and chemistry teachers' understandings of chemistry to be in a very real sense 'better' than those of students just meeting the subject.

Yet, it is certainly true that scientific ideas are not immune from influence by external factors. It is commonly said that there are seven colours in the rainbow, although most people find it difficult to clearly distinguish seven different colours. It is suggested that Newton was primed to see seven colours because of the significance of the number seven in his religious thinking. This may be apocryphal, but there is little doubt that Soviet genetics under Stalin drew on Lamarck's notion of inheritance of acquired characteristics rather than Darwin's theory of natural selection. Darwin's ideas were not considered consistent with Marxist notions of socialism, and so were not acceptable. Unfortunately, attempts to develop new strains of grain to feed the vast population based upon theories that were politically acceptable led to mass starvation. In this case, the attempt to conceptualise nature as certain people would like it to be, clearly failed. However, there *is* an important sense in which we have to recognise the artificial nature of our scientific concepts.

Do oxidation states exist in nature?

The world certainly seems to have some regularities that allow us to talk about 'laws of nature'. However, the concepts we use to describe nature are just our best attempts to make sense of these perceived regularities. So, for several centuries our best model of gravity was based on an inverse square law describing the attraction between masses. This 'law' of nature worked pretty well most of the time, but there were some anomalies where the law could not be made to fit data. It is now thought that gravity is better understood in terms of the geometry of space-time, and this very different approach seems to have solved some of the long-standing problems with the earlier model. Presumably gravity has not changed, but our best attempts to conceptualise it have. Perhaps the new model really is a good

description of how the universe works: but all we can ever do in science is develop models and then test them to see how well they fit our observations. We always have to be aware that a new experiment, or context, could show that our ideas fall short in some circumstances.

In chemistry, we have a wide range of concepts that help us make sense of regularities in nature. A good example is the Periodic Table, which sets out the chemical elements. The distinctions here – copper is different from iron, and we do not get difficult cases that we are not sure about, at least if we are dealing with pure elements – seem to fit reliably with experience. The notion of the elements must be a good candidate for a scientific model that maps onto the world in very reliable ways.

Other chemical concepts may be less convincing. A sceptic might ask whether acids exist in nature or are just a human fiction. The chemist would reply that there are a range of substances that show sufficiently similar behaviour to justify grouping them together and labelling them as a certain kind of stuff – and we use the label 'acid'. But the most useful way of deciding what is an acid has changed over time: so if acids themselves exist in nature, our conception of what counts as an acid is certainly not fixed. We should note this is a little different from the example of gravity, discussed above. We may feel we are getting closer to an effective understanding of what gravity is; but this does not apply in the same way to our concept of acids. The definition of acids has not changed because we have got better at recognising and characterising acids, but because we have changed our minds about *the most useful way* to define the concept. Antimony pentafluoride, SbF_5 , did not change its chemical properties to join the acid club: we changed our criteria for granting membership.

This clearly applies to many other chemical concepts: substances that we now consider oxidising agents went about their chemical business (metaphorically speaking) before the notion of oxidation was coined, and of course group membership here has again changed over time as our notion of how it is *most useful* to define oxidation has changed. Oxidation numbers, however, just did not exist until they were invented as a useful way of thinking about some chemistry. We should also recognise that some such changes have been less about us knowing

more about the chemistry found ‘in nature’, and more about us testing out chemical behaviour under conditions that may never have existed before we developed laboratory techniques.

For example, the notion of the molecular ion is very useful in mass spectroscopy, but is some way removed from being needed to explain any regularity in the material world that would be observed in the everyday surroundings of most typical 11-year-olds. Similarly, the notion of chemical shift as detected in nuclear magnetic resonance does not – despite the name – directly relate to any perceivable chemical properties of substances. Indeed, many of the concepts of chemistry have been invented to help answer questions that only chemists would ask.

So in school, over a period of a few years, students generally meet conceptual material that was developed over decades, and in some cases centuries, and much of which is *only* meaningful in the context of particular chemical problems that are not genuine issues for our students. In some ways, chemistry is at a real disadvantage here compared to both physics and biology, where many of the key concepts can clearly be related to real (if sometimes trivial or minimal) concerns in the students’ life. That is not to suggest that chemistry is not highly significant in children’s lives, but just that many of its applications tend to be less readily obvious.

Context-based courses attempt to provide students with relevant contexts in which issues can be raised that provide a motivation for developing chemical concepts. However, doing this in a way that does not seem contrived, and that allows the logical structure of the subject to be clear to students, can be challenging. The relevance of the concept of moment in physics can be demonstrated by having students open and close doors by applying force near the hinges. In biology, many students have a natural interest in their bodies and how they work. We might think that chemistry is about the material world, and that this clearly impinges on students’ lives in myriad ways. Actually, school chemistry tends to have little to say *about materials*, as its subject matter is somewhat more obscure.

The abstract nature of most chemical concepts

Chemistry is fundamental to materials science, but unfortunately being fundamental makes it one step removed from common materials. Most materials

that students are familiar with – cotton and other fabrics, many ‘plastics’, wood, air, commonly used alloys such as steel and bronze, adhesives, ‘flesh and bone’, and so forth – are complex and composite. In chemistry, however, we focus on pure substances. There certainly are some substances around that our students will have come across: water that is fairly pure, iron before it starts to rust. But most of the materials found in living organisms, those used in constructing our artefacts, and indeed most minerals that people usually come across when outdoors, are more complex than that. Understanding the nature of such complex materials is usually advanced work, building upon an understanding of the primary concerns of chemistry as a science: the nature and behaviour of pure substances.

This immediately makes the subject somewhat abstract. Consider a very simple example: what would happen if an ice cube and some iron powder were left in separate beakers for a period of time. The ice would change into water, and the iron would seem to change into rust. The former change is likely to seem more dramatic to many youngsters, as water obviously has very different properties to ice. Yet to the chemist, the former change is actually ‘only’ a phase change, and the two materials – ice and water – are *the same substance*. However, the rusting of iron is not a change in iron at all, but a reaction with other substances leading to something chemically distinct.

Explaining with quanticles

To appreciate why the second of the above changes is a chemical reaction but the first is not goes well beyond what the observer can see. Indeed, the chemist tends to conceptualise the distinction using abstract models that provide explanations in terms of hypothetical entities such as molecules and ions. The same water molecules exist after ice has melted, just in a different arrangement. In the rusting of iron, oxygen molecules are changed into ions and so forth.

So, unlike in school physics or biology where particle models make occasional appearances in some topics, the basic explanatory framework of most of chemistry is in terms of atoms, electrons, molecules and ions and how they interact and are arranged. These particles are nothing like the particles that students have previously come across – grains of salt, specks of dust – but are

rather quanticles: entities without definite surfaces but made up of fuzzy fields. There is a sense in which every tiny atom fades out to the edge of the universe and overlaps with every other atom, although it is usually better to ignore that and pretend that atoms have a definitive size! (This is why it is not possible to find *atomic* radii in data books – only covalent radii, metallic radii, van der Waals radii and so on.)

In teaching chemistry, we make constant shifts between talking about real substances and the quanticle-level models that we use to explain why the magnesium reacts with the acid, why the sulfur burns or why the colour of the copper sulfate crystals fades when they are heated. These explanations are often in terms of electron movements, bond making and breaking and so forth. And as the chemistry gets more advanced we introduce valence shell electron pair repulsion, hybridisation of atomic orbitals, resonance structures, electronic conduction bands, expanded octets, the presence of partially filled *d*-orbitals, nucleophiles, hyperconjugation, and a vast range of other theoretical notions to explain subtleties of substance behaviour. This constant oscillation between talking about actual substances that students can see and touch (or at least prod with spatulas and glass rods) and explanations in terms of quanticle models has been well recognised as one of the major causes of learning difficulties in the subject (Gilbert and Treagust, 2009).

Part of the problem is that for the teacher of chemistry the electrons, bonds and orbitals are very familiar (and so easily visualised) and, for those of us who have been chemists for a long time, these entities seem as real as the glassware and reagents that the students can see. For most learners, of course, these hypothetical entities will seem much less familiar than Snow White, the Mario brothers or Vulcan science officers on starships – and certainly harder to relate to. This can make it quite difficult for teachers to judge when students are really understanding the particle-based explanations *as intended*.

An additional complication is the technical language of chemistry – both the new vocabulary and the chemical formulae used to label substances. When a teacher refers to ‘oxygen’ or writes ‘O₂’ on the board this can refer to either the substance or to a single molecule. In teachers’ explanations, such ambiguity facilitates ready shifts back and forth from talking about the bench chemistry to

the quanticle-level models, but it also means the students have to pay careful attention to know when a label refers to a sample of the substance and when to a single quanticle (Taber, 2009b).

Just models

Finally, it needs to be recognised that no matter how familiar the chemistry teacher may be with atoms and molecules, with covalent bonds and resonant structures, and with reaction profiles and mechanisms, these are only explanatory *models*. The most advanced models we have are based on quantum theory and these suggest that many features of the models taught and learnt in school chemistry (and beyond) are limited in their fit to our current best understanding of chemical structures. As one example, assigning electrons in many-electron systems to discrete orbitals based upon the hydrogen atom (such as the sodium atom having an electronic configuration of $1s^2 2s^2 2p^6 3s^1$) does not seem to be justified in terms of our best understanding of the science. Yet these ‘outdated’ models are still retained because they remain very useful to chemists (Sánchez Gómez and Martín, 2003): just as we still teach the inverse square law of gravitation, which remains useful in most contexts.

This becomes very important if we forget to ensure students understand the nature and status of chemical ideas as models. If, as they pass through school, they are taught useful models (that gas molecules bounce off each other without otherwise interacting; that electrons are found in shells around the atom; that there are two types of chemical bonding) that they take as ‘facts’, but which are later contradicted (hydrogen gas reacts with chlorine gas; electrons occupy orbitals with complex geometries; most compounds have bonding that does not match covalent or ionic ideals), this can be a source of intense frustration and disillusionment. This can be avoided if students appreciate that chemistry builds up sequences of models of increasing sophistication, which have their distinct ranges of application.

The nature of students’ ideas in chemistry

Given the challenge of the teacher’s job in helping students develop chemical concepts, it should not be surprising that students commonly fail to grasp the intended meaning of many concepts. Sometimes they just do not manage to make any sense of an idea, and no meaningful learning is achieved. Often, however, the student does make sense of the

idea in terms of their existing prior knowledge, and this is when ‘misconceptions’ are formed.

Perhaps a good example of what is normally considered a misconception is the first idea in my list of examples above: that *the product of any neutralisation reaction is neutral* (Schmidt, 1991). This has been reported as a common alternative conception among students. Hans-Jürgen Schmidt has referred to this example in terms of the label ‘neutralisation’ being a ‘hidden persuader’. The chemistry teacher knows that it is the *relative strengths* of the reacting acid and base that determine whether the product will be neutral, but to students the labelling of a process as ‘neutralisation’ is likely to suggest that this is a process that necessarily produces something neutral. The student, in making sense of teaching, draws what would seem to most people a reasonable inference. As students normally meet neutralisation reactions in the context of strong acids reacting with strong bases, such as hydrochloric acid reacting with sodium hydroxide, they will have little reason to doubt their false assumption. Only at a later stage of their chemical education, once the notion has become well established in their thinking, are they likely to meet examples of neutralisation that do not give neutral products and so offer a basis for them realising their mistake. Or perhaps it is our mistake for calling a process neutralisation when it does not necessarily lead to something neutral?

The second example in my list would seem to be rather different. My colleague Dr Alejandra García-Franco from the National Autonomous University of Mexico interviewed several dozen English secondary students a few years ago to see which phenomena (such as salt dissolving, precipitation of silver chloride) they would explain in terms of particle ideas. The research was undertaken at a time when the English National Curriculum specified chemical knowledge in some detail, and the Government’s framework for teaching lower secondary science specified ‘particles’ as one of the five key ideas around which science teaching should be based (Key stage 3 National Strategy, 2002). We found that particle ideas *were* used in many student explanations, but mostly not in ways that matched the ideas taught in the curriculum (García Franco and Taber, 2009).

No doubt some of the examples of unconventional thinking we identified resulted

from alternative conceptions, ideas that the students had acquired and then learnt, and now applied when asked about chemistry. However, it also seemed that often the students were not reporting well-established conceptions, but rather falling back upon their ‘gut instincts’ about the material world to make sense of what Alejandra was showing them. So Katherine (a year 9, age 13/14, pupil) told Alejandra that ‘*when you put two things together they will always react*’. Sure enough, Katherine thought that water and ethanol being mixed was a reaction, and that salt dissolving in water was reacting. Yet when she was shown food colouring being added to water, Katherine did not suggest this was a reaction, but just the dye ‘spreading out’. So for Katherine, ‘*when you put two things together they will always react*’ was not a rule she always applied, but just one way of trying to make sense of different things she saw in chemistry. Often when we add things in chemistry lessons, there is a perceptible change, which students often just see as one chemical ‘reacting’ to another (which is not what chemists mean by a reaction of course).

The study suggested that quite a few of the explanations that students offered were more about appealing to intuitions (tacit feelings about what seemed to be going on) than being reports of firmly held conceptions. The students still offered explanations that were ‘wrong’ from a chemical perspective, but if much of their thinking about chemistry is based upon this kind of ‘implicit’ knowledge, then teachers who are aware of the different intuitions that students draw upon could perhaps channel thinking by triggering the most helpful intuitions in different chemical contexts (rather than seeking to ‘challenge’ ideas that students are not systematically and consciously applying). This direction for research is still in its early stages, but offers some promise for informing teaching.

My third example of a misconception is an explicit alternative conception that was held by one of my own A-level students, Annie (Taber, 1995). Somehow, by the start of her A-level course, Annie (age 16) had come to interpret the ‘+’ and ‘-’ symbols used to refer to electrical charge as meaning deviations from a full shell or octet structure. So for Annie it was Na^+ and Cl^- that were atoms, whereas Na and Cl represented the ions with their ‘full electron shells’. Moreover, Annie completed most of her two-year A-level

course before I diagnosed this misconception. She managed to misinterpret what her teachers, textbooks, and classmates meant by these symbols, without appreciating there was any problem: an idiosyncratic example of how – in making sense of what others are telling us – we commonly manage to unintentionally distort their intentions.

By contrast, my fourth example reflects a common misconception. To the chemist, the ionic model of bonding explains such features as solubility of salts, conductivity of salt solutions, high lattice energies, high melting temperatures and so on in terms of a continuous network of strong bonding throughout the lattice. In NaCl, each ion is bonding to the six closest neighbours, which are in turn each bonded to their six closest neighbours. Appreciating the chemical ‘problem’ (explaining the properties of the substance) allows the chemistry teacher to understand the solution (the ionic lattice).

Yet, during secondary education, students taught about ionic bonding commonly come to understand it very differently (Taber, 1997). For many students the NaCl crystal contains molecule-like ion pairs that are ionically bonded internally (and that are found together in solution), but are only weakly attracted to other ion pairs. Such a structure would not explain the properties of NaCl, but that does not prevent students commonly understanding its structure in terms of a ‘molecular’ framework where the ion pairs are considered to be like molecules of NaCl. Students commonly suggest that the elements sodium and chlorine can only form one bond, because their atoms can only donate/accept one electron, and that the ionic bond only exists between a sodium ion and chlorine ion formed by electron transfer between them.

According to this way of thinking, a sample of sodium chloride produced by neutralisation would not have *any* ionic bonds (as the sodium ions and chloride ions were already present in the hydrochloric acid and sodium hydroxide solutions), but students do not tend to spot this, and rather assume that electron transfer is taking place during the reaction.

Many misconceptions in science have clear origins in everyday experience. Physics teachers can blame common experience for most students thinking that moving objects come to a stop unless a force is continuously applied (as, in practice, this is what happens – the resistive forces operating are seldom recognised) and appreciate

that the laws of motion are counter-intuitive. Similarly, a biology teacher can appreciate why many students think that plants grow by taking in material from the soil by the roots, which seems a sensible assumption given the use of fertilisers and ‘plant food’. But it is not possible to explain students’ thinking about ionic bonding in terms of everyday experience.

The use of NaCl as the formula for sodium chloride (suggesting discrete units of NaCl), rather than perhaps Na_6Cl_6 (reflecting the extended ionic lattice of innumerable ions), may be unfortunate here. It is also likely that if covalent bonding is taught before ionic bonding, this may well cue students to think in terms of small molecular-like units. However, careless talk about bonds forming because atoms need or want to fill their shells would seem to be a major culprit. The notion that reactions occur and bonds form so that atoms can complete their octets or shells appears to be a myth that students readily adopt and then widely apply. So it has been found that most A-level students will explain the reaction between H_2 and F_2 (substances existing as molecules) in terms of the atoms wanting to share electrons to get full shells! So electrovalency tends *not* to be understood in terms of the charge on an ion of an element, but rather (in analogy with covalency) as a measure of how many (ionic) bonds can be formed by electron transfer.

This alternative conception is not an isolated idea, but part of a coherent alternative conceptual framework that students adopt to explain why reactions occur and why bonds form, and that derives in a large part from our teaching of the subject in ways that mislead students (Taber, 1998). Perhaps the most unhelpful example of poor teaching in this regard is a commonly seen diagram that shows a single electron-transfer event between isolated atoms to form a pair of ions (a chemically unlikely event) being labelled as showing ‘ionic bonding’: a careless error that I have even seen in national exam papers. Such diagrams are readily adopted by learners (for instance, see Figure 1, which was drawn by an A-level student).

The message here is that we should be able to avoid or reduce such misconceptions by more careful planning and sequencing of our teaching. By thinking at the learner’s resolution, for example, we can highlight the fact that NaCl is a misleading symbol when it is introduced and reiterate this when it is revisited in our teaching.

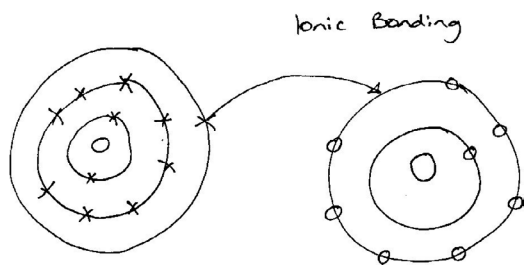


Figure 1 A learner's notion of ionic bonding

For the student, the world of atoms, electrons, ions and molecules is abstract and unfamiliar, and only accessed through teachers and teaching materials. The teacher is well aware that ionic bonding should not be confused with electron transfer, and should know that interactions between neutral atoms (as in Figure 1) rarely have any relevance to chemical processes of interest. But if our teaching can be interpreted otherwise, it is hardly surprising that students develop alternative conceptions of the subject.

My final example of a chemical misconception is included to emphasise this point. Sodium is a metallic element and to a chemist the metallic elements tend to form compounds where they are present as positively charged cations. Most ions met in school science have charges of -1 , -2 , $+1$ or $+2$, with just a few having a higher magnitude of charge (Al^{3+} , PO_4^{3-}). Sodium is only met in school as the $+1$ cation (in the metallic lattice, in solution, in various salts). To the teacher with some insight into chemistry this should suggest that in most viable chemical environments the stable sodium species is Na^+ . A sodium ion with a higher magnitude of charge, or with a negative charge, would be a very unexpected species in school chemistry.

So, can I really justify suggesting that there are students who think that *the Na^{7-} ion will be more stable than the Na atom*? When A-level students were asked to make simple comparisons (for example between the species shown in Figure 2), I did indeed find just this. Students from different schools and colleges were asked to make this comparison in a series of small-scale studies. In each case, most of the students thought the $7-$ anion would be *more stable* than the atom (Taber, 2009c). Indeed, there were clear majorities in each case (21 out of 29 students in one study, 17 out of 19 and 21 out of 33 in the others).

Of the chemical misconceptions I have come across, I find this particular example the most telling. It offers a case where most students have developed a strong belief regarding something they can surely only have learned about in their chemistry lessons, and yet the clear majority develop a conception that seems ridiculous and bizarre to the chemistry teacher. The common rationale, of course, is that atoms will do whatever they can to lose or gain electrons so that they can obtain a full shell. To many students this heuristic rule is more salient than other considerations (such as how an ion with a $7-$ charge holds together), and few actually spot that Na^{7-} does not actually even have a full electron shell.

Conclusion

This article has only been able to 'scratch the surface' of the research into learners' ideas in chemistry. It is clear that the chemistry teacher has a challenging task to help students make sense of the wide range of models and theoretical entities that we use in chemistry. These ideas are often abstract and complex and are the solutions to problems that can often only be fully appreciated in a particular historical context. Given that so many of the chemical models relate to quantiles that students cannot directly experience, the learner has to find ways to make sense of teaching, drawing upon analogy, visual clues, or various intuitions about the way the material world works (see Taber *Typology of learning impediments* webpage). Perhaps not surprisingly, students regularly develop ideas that do not match chemical knowledge.

Educational research offers some help here. Many of the most common misconceptions have been well described, so that teachers no longer need to be surprised when students offer apparently bizarre suggestions (such as

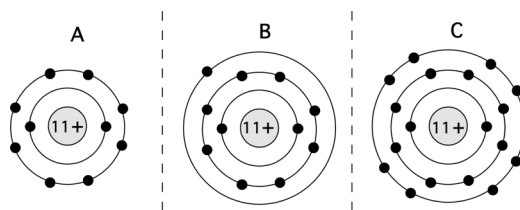


Figure 2 Which of these species would be stable? (A: Na^+ ion; B: Na atom; C: Na^{7-} ion)

Na⁷⁻ being stable). Research is also beginning to uncover more about why particular ideas are first adopted. Intuition plays a role here, as students seem to interpret the abstract models they meet in terms of their gut feelings about the world, which can over time develop into firmly held alternative conceptions and more extensive conceptual frameworks. Hopefully further research can be used to show teachers how to channel and harness such intuitions to avoid misconceptions and build up the most useful ways of thinking in chemistry.

The most important advice to teachers, however, is to learn as much as possible about the way *your* students understand chemistry and to teach accordingly. By appreciating how the chemistry and the teaching models we use are understood at the learner's resolution, we have the best chance to avoid inadvertently encouraging common misconceptions. The most significant finding about student misconceptions in chemistry is that so many of them must derive to a significant degree from teaching that was not understood as intended.

References

- Duit, R. (2007) *Bibliography – students' and teachers' conceptions and science education*. Kiel: IPN. Available at: www.ipn.uni-kiel.de/aktuell/stese/stese.html
- García Franco, A. and Taber, K. S. (2009) Secondary students' thinking about familiar phenomena: learners' explanations from a curriculum context where 'particles' is a key idea for organising teaching and learning. *International Journal of Science Education*, **31**(14), 1917–1952.
- Gilbert, J. K. and Treagust, D. F. ed. (2009) *Chemical education: linking the representational levels of chemistry*. Dordrecht: Springer.
- Key stage 3 National Strategy (2002) *Framework for teaching science: years 7, 8 and 9*. London: Department for Education and Skills.
- Kind, V. (2004) *Beyond appearances: students' misconceptions about basic chemical ideas*. 2nd edn. London: Royal Society of Chemistry. Available at: www.rsc.org/education/teachers/learnnet/miscon.htm
- Kind, V. and Taber, K. S. (2005) *Science: teaching school subjects 11–19*. London: RoutledgeFalmer.
- Sánchez Gómez, P. J. and Martín, F. (2003) Quantum versus 'classical' chemistry in university chemistry education: a case study of the role of history in thinking the curriculum. *Chemistry Education: Research and Practice*, **4**(2), 131–148.
- Schmidt, H.-J. (1991) A label as a hidden persuader: chemists' neutralization concept. *International Journal of Science Education*, **13**(4), 459–471.
- Taber, K. S., *Typology of learning impediments* webpage: people.pwf.cam.ac.uk/kst24/ScienceLearningDoctor/SLDTypology.html
- Taber, K. S. (1995) Development of student understanding: a case study of stability and lability in cognitive structure. *Research in Science and Technological Education*, **13**(1), 87–97.
- Taber, K. S. (1997) Student understanding of ionic bonding: molecular versus electrostatic framework? *School Science Review*, **78**(285), 85–95.
- Taber, K. S. (1998) An alternative conceptual framework from chemistry education. *International Journal of Science Education*, **20**(5), 597–608.
- Taber, K. S. (2002) *Chemical misconceptions – prevention, diagnosis and cure: theoretical background*. Vol. 1. London: Royal Society of Chemistry.
- Taber, K. S. (2006) Teaching about ideas and evidence in science – towards a genuinely broad and balanced 'science for all'. *School Science Review*, **87**(321), 26–28.
- Taber, K. S. (2009a) *Progressing science education: constructing the scientific research programme into the contingent nature of learning science*. Dordrecht: Springer.
- Taber, K. S. (2009b) Learning at the symbolic level. In *Chemical education: linking the representational levels of chemistry*, ed. Gilbert, J. K. and Treagust, D. F. pp. 75–108. Dordrecht: Springer.
- Taber, K. S. (2009c) College students' conceptions of chemical stability: the widespread adoption of a heuristic rule out of context and beyond its range of application. *International Journal of Science Education*, **31**(10), 1333–1358.

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