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10. Constructing chemical conceptions

This final chapter reviews the ideas presented in earlier chapters and discusses how these ideas may be used to help students construct meaningful and acceptable versions of scientific concepts. The limitations of many student texts are considered, and some specific vignettes of classroom learning are used to illustrate key principles about teaching and learning. In conclusion the principles of constructivist teaching are reviewed.

Principles of constructing knowledge in the classroom

This publication has been written from a perspective – based on research into how learning occurs – known as ‘constructivism’.¹ This approach can be summarised in a few simple principles:

1. People naturally, and actively, learn from their experiences, including, but by no means exclusively, experience in the classroom.
2. Our brains are not equipped to take on board large amounts of learning wholesale, as we have to process information in a limited ‘mental scratch-pad’.
3. Therefore we need to break down information into manageable chunks that do not exceed the student’s processing capacity...
4. ...before being later ‘reassembled’ into useful knowledge (and thus the references to constructing knowledge).
5. Meaningful learning occurs when we can make sense of new information in terms of what we already know.
6. Therefore the ‘meaning’ of new information is heavily determined by prior learning.
7. Students have already acquired a lot of ideas about scientific topics from their own practical experiences, and their interpretation of what they have been told, before they study those topics in school. This prior knowledge acts as the foundation on which new learning is constructed.

An experienced teacher comes to class with a vast storehouse of relevant ideas and knowledge relating to the topic being covered. In particular the teacher has an overview of the wider conceptual framework within which the ideas fit.

The student usually arrives in the same class with a much more limited and incoherent knowledge base about the topic, having conceptual frameworks that may include key omissions, major fractures and intrusions of alternative notions from various sources (see Chapter 4). Each individual student brings their own set of associations for words to class (see Chapter 3), and makes their own interpretation of what the teacher says (eg Figure 10.1).

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Figure 10.1 Students' interpretations and associations may vary

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It is not surprising that what seems clear, simple and logical to the teacher may sometimes seem confused, complex and arbitrary to the student. Once we learn to recognise a pattern as a gestalt (of an atom, of an equation for neutralisation, etc) it requires a deliberate effort to decompose it into its constituent parts (see Figure 4.1). A gestalt is an organised whole in which each part affects every other part, the whole being more than the parts. It is difficult for the teacher to see the subject matter at the resolution available to the student.

What is more surprising, perhaps, is how sometimes students may continue to make sense of the teacher's ideas despite the most fundamental 'misconceptions'. As an example, consider the case of Annie, who held an alternative conception of ionic charges.

Vignette 1: The case of the deviant charges

When Annie enrolled on a post-16 chemistry course she already knew about ionic charges from her study of school science. Annie knew, for example, that the sodium ion was shown as '+1', Na^+ , and the ion of chlorine as '-1', Cl^- . However, Annie's interpretation of these charges was unusual. For Annie, the signs indicated deviations from a full shell electronic structure.

For Annie, Na^+ had a +1 charge because it had electron configuration 2.8.1. It had one electron over a full shell, indicated by the +. In a similar way, Annie thought that Cl^- had a configuration of 2.8.7, as the '-' indicated (to Annie) that this species was one electron short of a full shell. During nearly two years of post-16 chemistry Annie managed to interpret the teaching, and the comments of her classmates, in terms of her deviation charges.

Annie managed to make sense of ionic bonding from her own perspective, and was even able to suggest balanced ionic formulae – although not necessarily balanced in conventional terms. Her suggested stoichiometry for aluminium sulfate was $\text{Al}_4(\text{SO}_4)_2$ because to get a neutral compound 'you'd have to use, say four aluminiums, and, two, sulphates'. This incorrect answer was not due to a

miscalculation, as Annie was able to explain why $(\text{Al}^{3+})_4 (\text{SO}_4^{2-})_2$ should be neutral.

In terms of her 'deviation' charges each Al^{3+} ion had three extra available electrons, and each SO_4^{2-} ion was lacking two electrons. Four aluminium ions provided 12 electrons, and the two sulfate ions accepted four of these to make up octet structures. This would seem to leave eight 'extra' electrons, but from Annie's alternative scheme this could be ignored,

'That'd make eight. It would make eight, so it would be neutral. Anyway it would give you eight, eight plus. [Interviewer: Would that be neutral?] A neutral charge ... because it would become nought.... if you had eight plus it's like having eight minus, you don't really have that because you have your shell with all your electrons in it, which could be eight.'

In other words, as deviation charges indicate a deviation from an octet, then eight electrons – an octet of electrons – counted as neutral. Annie's electron arithmetic only had to take count of the remainder when counting in base 8.

Amazing as it may seem, Annie's alternative take on ionic charge went unrecognised during most of her time in college. Neither her teachers, nor she, realised that they were talking across each other. Had Annie not been interviewed in some depth about her understanding of key chemical ideas shortly before her external examinations, then her alternative conceptions would probably never have been diagnosed. Even then Annie found it difficult to switch to the conventional scheme as her alternative ideas were well established, and had made sense to her.

The importance of diagnosing learners' ideas

To the teacher the signs '+' and '-' relate to electrical charges that students would be expected to know about from their study of physics topics in school. However teachers cannot assume the expected prior learning will be in place. As was found in Chapter 7, students may either be ignorant of the physical principles, or may simply not bring them to mind and apply them in a chemistry context.

The notion of being a 'learning doctor' was introduced in Chapter 4. Annie's alternative interpretation of 'deviation' charges was not a common conception that a teacher might have specifically been prepared for. If Annie's knowledge had been effectively audited at the start of her post-16 course then her alternative conception may have been diagnosed, and 'treated' early in her course. Students in subsequent post-16 chemistry classes in Annie's college were asked to undertake a set of induction exercises, which elicited a wide range of null learning impediments ('gaps' in the expected knowledge) and alternative conceptions of the fundamental chemical ideas that these students should have mastered during their earlier schooling.²

The importance of formative assessment, testing to determine what learning objectives are yet to be achieved, is now being recognised as very important,³ and teachers are being urged to adopt strategies 'to explore pupil's progress and to help pupil's learning'.⁴

'Missing' learning, and alternative conceptions can be major causes of learning difficulties for students (see Chapter 4). Auditing prior knowledge, and, in particular, diagnosing substantive learning impediments, are activities which can be cost-effective in terms of time and effort, and which can help avoid some of the frustration felt when students fail to leave a well planned and executed lesson with the intended understandings.

The classroom materials included in the companion volume can help diagnose some of the common alternative conceptions in key chemical topics. However, the materials are necessarily limited. Anyone teaching chemistry to students in the 11–19 age range will hopefully find some of the materials relevant and useful – but it has not been possible to address the vast catalogue of alternative ideas reported in the literature,⁵ nor even to cover all the chemical topics met during this age range.⁶ (A large set of Concept Cartoons is available to initiate elicitation of student ideas and discussion in a wide range of science topics. Although aimed at the 7–14 age range, many of the Concept Cartoons are suitable for some older students as well.⁷)

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Building on the available foundations: only connect...

As well as discussing classroom materials in a number of fundamental topics, the previous chapters have illustrated an approach to teaching chemistry which takes into account key ideas about learning: the importance of matching classroom presentations to the students' existing level of knowledge; the need to break down material into manageable steps and to see the chemistry content at the student's 'resolution'; the importance of using aspects of existing knowledge to 'anchor' new ideas; the need to check students' interpretations and their meanings for words; the need to 'make the unfamiliar familiar' by using analogies where both similarities and differences are explored; and being concerned to find the optimum level of simplification that allows understanding now, without oversimplifying ideas so that they become learning impediments in the future.

A key aspect of this approach is knowing your students: knowing about the limitations imposed by their cognitive apparatus (such as working memory) and by their existing conceptual frameworks. Learners' ideas about science can be 'wacky', inventive and thought-provoking. They can also act as significant learning impediments (Chapter 4). They are, however, the only frameworks of understanding through which the teacher's words can be interpreted by the student; the only raw material available for building new knowledge, and the only substrate to which new ideas can attach. Reconstruction may often seem desirable – but simply ignoring the student's existing frameworks of knowledge is not a feasible option. Learning is largely about making new connections to existing conceptual frameworks: developing and extending the learner's internal 'concept maps' (see Chapter 3) stored within the brain.^{8,9,10}

Teachers' subject knowledge

So the teacher does not only have to have a good grasp of the science of chemistry, but also of the students, and of the subject pedagogy – the science of teaching the subject (see Figure 10.2).

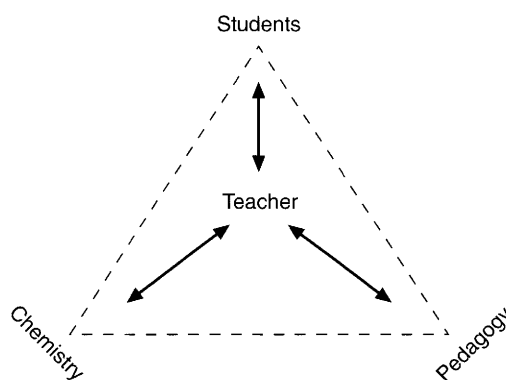


Figure 10.2 The effective teacher has to draw upon three distinct domains of knowledge¹¹

Educational research, of the type that has informed this publication, can inform teachers' pedagogic knowledge. Such research leads to advice on ordering subject material, pace of presentation, likely problems with 'missing' prior knowledge or alternative interpretations and so forth. The teacher's own classroom experiences can also provide a wealth of insights in these areas.

Each class, and each student, is unique, so teachers need to be able to apply their pedagogic expertise in ways that are responsive to the needs of each learner – including students like Annie who come to class with ideas that are idiosyncratic. Published probes may not be available that will elicit such unique ideas, and teachers need to have honed their diagnostic skills as a learning-doctor (Chapter 4).

The third domain of knowledge that is important for the teacher is, of course, the subject knowledge itself. Although most teachers are highly informed about many aspects of their subject, it would be unrealistic to expect all science teachers to be experts in all areas of the science curriculum. Recently

trained teachers in the UK are officially expected to demonstrate such expertise,¹² but even here one would expect some imperfections! Teachers, of all people, should value learning, and see themselves as life-long learners, with scope for developing their expertise.¹³ Given that it is inevitable that teachers will have their own alternative conceptions and knowledge ‘blind-spots’, it seems sensible to encourage teachers to explore and develop their knowledge, rather than create an assumption of omniscience where practitioners can not openly admit to having an imperfect knowledge base.¹⁴

I remember having a disagreement with the Head of Chemistry in my first job. The topic of strong acids arose, and my colleague mentioned that strong acids had a pH value of 1. When I suggested that this was not always the case, he disagreed. I argued that strong acids could have a pH of less than 1 (which did not show up on the indicator paper used in the school laboratories), and that when diluted sufficiently the pH would rise above 1. This was clearly seen as a rather heretical suggestion. However, being reasonable people, we met in the laboratory at lunchtime and undertook sequential dilutions of a sample of bench acid until there was no doubt that the pH value was rising well above 1. The point is not that a teacher had an alternative conception, but that he was prepared to learn.

Of course there is a difference between teachers actually holding alternative conceptions and just having slightly distinct perspectives on a topic. In Chapter 2 we found that teachers could not agree on the accuracy of definitions of some very basic chemical terms – but this need not imply that some of these teachers did not know what is meant by the terms molecule, element and so forth.

In Chapter 3 ‘the’ structure of chemistry was discussed, but just as students’ conceptual frameworks will not match the curriculum version of the subject, individual teachers will hold in their cognitive structures unique versions of ‘chemistry’, each idiosyncratic and imperfect sub-sets of the formal structure of the subject. The teachers’ mental concepts maps will be much more sophisticated, extensive and reliable than those of the students – but hardly encyclopaedic.

Learners’ common alternative conceptions about chemical bonding were considered in Chapter 8. One key point made there is that students who learn about chemical bonding as being either ionic or covalent may find it difficult to later accept any other classes of bond. Some teachers may have sympathy with the students’ views. Indeed an established and respected science educator has suggested to me that he did

‘not really feel that metallic bonds are first rate chemical bonds – more the case of groups of metal atoms ‘making the best of a bad job’. Hydrogen-bonds are certainly ‘inferior’ and I have some sympathy with the student who dismisses them as ‘just a force, and not a real chemical bond’ ‘.

However, the teacher’s developed view is that there are graduations of bonding – where the student’s less sophisticated approach is likely to be that examples that do obviously meet the criterion of filling electron shells are simply not bonds.

Of course, the formal structure of chemistry is an abstraction that does not exist in any one place. If teachers’ versions are imperfect, then most practising chemists are likely to hold even less satisfactory versions of the subject – up-to-date and detailed in their immediate field, but often quite limited in areas of the subject that they have not had reason to think about for years or even decades. If ‘the’ current structure of chemistry can be said to exist anywhere, it is in the research literature of the subject – but few teachers can update their knowledge from the primary sources.

Textbooks as flawed authorities

Most teachers are likely to use student textbooks as their sources for checking information. Such textbooks are often written by practising teachers or by those who have taught, and are used by teachers to gauge the level of presentation needed. In Chapter 4 it was suggested that some substantive learning impediments (students’ alternative conceptions and alternative frameworks) may be labelled as ‘pedagogic’. In simple terms, some alternative ideas which block intended learning actually derive from the teaching of the subject itself.

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Many of the alternative conceptions discussed in this publication can either be found in student textbooks, or can at least be understood to be encouraged by such texts. A relatively cursory examination of a range of recently published books quickly revealed many examples of incorrect, dubious or unhelpful presentations.

Unhelpful descriptions of macroscopic phenomena

Students often have difficulty with the notion of acid strength because they reasonably assume that strong means concentrated (see Chapter 2). One textbook attempts to clarify the topic with the following introduction:

‘Acid strength is different to how strong or weak an acid is; it is a measure of how much acid a solution contains, not how strong the actual acid is.’¹⁵

It is hard to see how this statement helps any learner make sense of the chemical distinction.

Another area of student difficulty is learning about chemical equations (see Chapter 9). Often equations given in student books do not clearly distinguish the material aspects and the non-material ones, *ie* energy is included in an equation using the same type face used for the substances. To give just one example,

fuel + oxygen → oxides + heat + light

In this case the oxides, heat and light were collectively described beneath the equation as ‘the things [sic] that we end up with’.¹⁶ As it is known that students do not always distinguish between matter and energy terms (see Chapter 6), this must be considered an unhelpful way of representing the chemical process.

Another book tells readers that ‘a convenient way of writing down what happens in the reaction between zinc and dilute hydrochloric acid’ is

‘**zinc** + hydrochloric acid → **zinc chloride** + hydrogen’¹⁷

There is no explanation (or obvious rationale) for the decision to emphasise some parts of this equation in bold type. The term ‘salt’ is printed in bold type further down the page, so this equation could have been meant to be read:

zinc + hydrochloric acid → **zinc chloride** + hydrogen

This interpretation is pure conjecture, and, even if correct, students could hardly be expected to realise this. Clearly the use of such texts requires careful support from the class teacher.

Unhelpful descriptions of the molecular world

If textbook treatment of macroscopic phenomena may be unhelpful, attempts to help students learn about particle models may be even more flawed. It is known that this is an area where students often have difficulty (see Chapter 6), and so clear and accessible texts would be helpful.

Definitions of basic chemical concepts may be problematic, but some books for students seem to offer definitions produced with little thought. Many examples were given in Chapter 2, but further examples can be found in more recently published texts. So one book describes the atom as ‘the smallest particle in an element’¹⁸, a description that might be seen to be just as applicable to a molecule, or an electron.

One book aimed at 12–13 year olds defines element in terms of ‘only one type of particle’ and compounds in terms of ‘more than one type of particle’, which would be appropriate for ionic compounds but not covalent compounds. Further on in the book ‘compound’ is re-defined as ‘two or more types of atoms chemically joined together to make a single type of molecule (particle)’.¹⁹ As well as appearing contradictory, this approach does not clearly distinguish the macroscopic and molecular levels. The transition is obvious to author, and teacher, but is not made explicit to the student reader. (Further examples of this type of sloppy approach are discussed below.)

Diagrams which are meant to clarify ideas, can potentially be just as confusing as carelessly written text. One book shows particles in a solid crammed together, and uses this model to explain properties of a solid. The diagram is repeated in a section called 'summing up' which reiterates that 'solids are made up of particles that are very close together'. On the facing page however, are two diagrams showing particles in a solid when it is heated. The text informs the reader that 'the particles begin to move further apart making the material bigger'. There is no discernible difference in the spacing of the particles before and after heating (which is realistic), just an attempt to show more vigorous vibrations about the lattice positions. However the particles in both figures are separated by significant spacing, so they are shown much further apart than the particles in previous diagrams showing solids and further apart than particles in diagrams representing liquids. Immediately following the diagram the text continues: 'The expansion of solids can cause a problem for designers.' It transpires this is a reference to designing bridges, but could equally apply to the graphic designers who prepared the figures.²⁰ The teacher will understand that the two different types of diagram of particles in a solid are used to make different points, but seen from the resolution of the learner, with a limited appreciation of the role of models in science (see Chapter 6), this contradiction must be very confusing.

It is not unusual for diagrams showing the relative particle separations in the three states of matter to represent the gas particles much too close together – sometimes separated by distances of only 1-3 particle diameters.²¹ One book has a diagram showing that 'air is a mixture of different gases' which represents molecules of nitrogen, oxygen, carbon dioxide and argon crammed together as if in a liquid – with most molecular separations being less than one atomic diameter.²² Another book has a similar picture showing 'air is a mixture of gases' with only marginally better spacing.²³ Perhaps the worst example examined was in a book for post-16 students, where diagrams showing 'the arrangement of particles in solids, liquids and gases' and 'the changes of state' showed the particles furthest apart in the solid and closest together in the gas – where, unlike in the condensed phases, two of the particles are shown to actually be in contact.²⁴

Sometimes the molecular level explanations given in students' books must seem very obscure to learners. In one book a figure illustrating the difference between a concentrated and a dilute acid solution had the following legend:

'More particles of acid collide with the marble in a concentrated solution than in a dilute solution. The fewer particles of acid must now [*sic*] move past particles of water to get to the marble.'²⁵

Perhaps this made sense to the author, but surely students are left to fill in too much information to attempt to understand this explanation.

A textbook spread about diluting solutions in one book uses orange squash as its example. Although some students might not initially realise that this is a mixture, the text refers to how 'the colouring and flavouring get spread out'. Later on the page students are asked to 'imagine that the orange drink is made of orange particles'. A diagram shows 'a really dilute solution with only one orange particle left in it'.²⁶ Although this is presented as a thought experiment, it does show the mixture as represented by a single type of solute particle which could be confusing. The text also suggests that 'the orange [squash] in the bottle contains a lot of orange particles, and not many water particles' which seems very unlikely for a solution. Moreover, the diagram shows particles so large that only five fit across the beaker. The ratio of orange particles to water particles is 1:50, which a 'back-of-the-envelope' calculation suggests is equivalent to a concentration of about 1 mol dm^{-3} . In the context of school science this would hardly be a 'really dilute solution'.

What is not clear in this particular case is whether the diagram showing 51 particles of the solution filling up the beaker is intended to represent the particles in the solution, or a macroscopic scale model. Teachers and authors are able to use a wide variety of modelling conventions, but as it is known that most students have naive ideas about modelling in science (see Chapter 6), it is important that the conventions used in such diagrams are made explicit for the learners.

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A diagram of glucose solution in another book shows the water molecules as having three separate spheres joined, but the glucose molecules as hexagonal structures the same size as the water molecules.²⁷ It is not clear why this type of representation was chosen, but if students know that the shape of the water molecules is meant to reflect the 'H₂O' structure with three atomic centres, then sharp corners on the same overall sized glucose molecules would seem to imply that they cannot be composed of the same sort of components as water molecules.

A common error in many books, that is often reflected by students, is that the third and subsequent electron shells, like the second shell, can only hold 8 electrons.

'Electrons are arranged around the nucleus in shells. Each shell can only hold so many electrons. The first shell can hold up to 2 electrons. The second and third can both hold up to 8 electrons.'²⁸

The logic behind the 2, 8, 18, 32... pattern is too abstract to be presented in school science. However, the simple notion that the larger the shell, the more (mutually repelling) electrons it can accommodate would seem accessible.

In one text for post-16 students 'covalent bonding in an iodine molecule' was represented as two overlapping circles with electrons as dots and crosses. The legend reported that 'only the electrons in the highest energy level [are] shown.' However, the accompanying diagram showed the 14 valency ('outer shell') electrons in the iodine molecule, *ie*, the six non-bonding ('lone') pairs and the bonding pair. The bonding electrons would, of course, be in a molecular orbital at a lower energy level than the electrons in effectively unperturbed sp³ atomic hybrid orbitals.²⁹ This is not a pedantic point when it is remembered that if the bonding and non-bonding electrons were at the same energy level the molecule would spontaneously dissociate. A diagram meant to help explain bonding actually undermines the physical basis of that very phenomena. Research shows that post-16 students may have difficulty distinguishing the concepts of electron shell, sub-shell, orbital and energy level (see Chapter 7) and inaccurate textbooks are only likely to exacerbate this.

Confusing the macroscopic and the molecular

The molecular model is extremely important in chemistry, although it is an abstract model that many students find difficult (see Chapter 6). Many explanations in chemistry require transitions between the macroscopic and molecular levels, when it is believed that such transitions place high cognitive demands on students.³⁰ Moreover, it is known that students often mis-apply the molecular model by ascribing macroscopic properties to the particles at the molecular level. This means that it is important for teachers to clearly distinguish between these two levels, and to carefully highlight when there are transitions between them. The same onus falls upon textbook authors. The necessary care is not always taken, so that student books include headings such as 'formation of ions from elements',³¹ and comments such as 'a formula shows the number of atoms of each element found in a compound'³².

Diagrams often confuse the two levels, sometimes apparently deliberately (as in the example of diluting orange squash discussed above). A diagram showing a metal sheet being rolled shows the number of particles in a thickness of metal before and after being milled. This is perhaps an attempt to emphasise that the size of individual particles stays the same, but students may not appreciate the schematic nature of the sheet thickness being reduced from 8–9 atoms to 2–3 atoms.³³

It is more difficult to appreciate the rationale behind a diagram of 'smoke particles [*sic*] bombarded by many air molecules' which shows one particularly irregularly shaped object, much like an asteroid in appearance, and seven smaller spheres. In its longest direction the 'smoke particle' has a length equivalent to four times the diameter of the 'air molecules'. Not only are the relative sizes completely wrong, but the highly complex shape of the smoke particle implies that it has a detailed structure at a scale much smaller than that of air molecules.³⁴

A diagram of a solution in one book shows the solvent molecules as spheres, but shows the solute particles as cubes, much like tiny salt or sugar grains. There is a coloured background between the

particles in the solution (which could encourage the alternative conception that particles are embedded in 'substance'). In a diagram showing filtration of a suspension, the suspended particles are shown as if macroscopic. A few pages later in the same student book a diagram of salt water solution has a flask of blue liquid with small, but visible cubes mixed into it.³⁵ As one final example, a diagram showing the action of enzymes in one book represents the enzyme as molecule-sized scissors (see the discussion of classroom analogies below).³⁶

Encouraging an atomic ontology

One particular alternative conception that was highlighted in Chapter 6 was the 'assumption of initial atomicity' – the idea that all chemical process occur between atoms. Yet many textbooks present their expositions as if chemistry does start with discrete atoms. Consider the following definitions,

'[atom] A particle of an element that can take part in a chemical reaction.'

'[compound] A substance made from the atoms of two or more elements that have joined together by taking part in a chemical reaction.'³⁷

Books may ask students 'how many chlorine atoms [sic] react with a single atom of magnesium?'³⁸, and commonly present diagrams representing reactions in terms of isolated atoms, even when one or more molecules worth of atoms are needed (four atoms of hydrogen with one of carbon; two atoms of oxygen with one of carbon).^{39,40,41,42,43}

This common type of misleading diagram may have been perpetuated because authors do not closely think about the actual process they are trying to illustrate, or perhaps there may be a deliberate attempt to simplify the real chemical reactions. Perhaps there is a third possibility – that sometimes the authors genuinely believe the explanations are valid (see below). Whatever the reason, such an approach conveniently allows authors to imply that there is a simple reason why reactions occur,

'When two non-metals such as chlorine and hydrogen react, they do it by sharing electrons. The diagram shows what happens to the shared electrons...A hydrogen atom has just 1 electron in its first energy level. A chlorine atom has 7 electrons in its third energy level. If the two atoms share 1 electron each...hydrogen can fill its first energy level and chlorine can fill its third energy level.'⁴⁴

Although the statement above is a fair description of the interaction between two isolated atoms, it is hardly surprising if students assume it is meant to relate to the chemical reaction between (molecular) hydrogen and chlorine. These types of statements often seem to include subtle 'sleight-of-hand' transitions between the macroscopic and molecular levels, during which discussion of isolated atoms is suddenly applied to the macroscopic substance (which are not atomic). Some textbooks explicitly suggest real chemical reactions can be explained in this way,

'How chemical reactions work:

All atoms, apart from the noble gases, will form compounds. When they form compounds, it's all to do with electrons. They try [sic] to make a full shell of electrons on the outside of the atoms.'⁴⁵

Note that in this example the narrative slips from the molecular level (atoms) to the macroscopic (noble gases, compounds), and then back (electrons, atoms).

'Why elements react to form compounds:

Atoms like [sic] to have each energy level either completely full or completely empty just like they are in the noble gases. The atoms are then more stable. This is why sodium reacts with chlorine.'⁴⁶

This statement is made so definitively that the student reader would not be expected to be expected to realise that the discussion of what 'atoms like' has no relevance to the reaction of (metallic) sodium and (molecular) chlorine. One wonders whether the authors of this statement may themselves actually believe this is a valid explanation.

The responses commonly obtained from the **Hydrogen fluoride** probe (see Chapter 9) are hardly surprising if students have been exposed to such texts. Not only is the implication that molecular materials react because of the unstable nature of atoms, but anthropomorphic language is used.

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In the following, final example, the rationale for reaction is related to energetics rather than some irrelevant consideration of the electronic structures of isolated atoms. Yet the notion of atoms reacting is still introduced (for no clear reason), and they are said to react with oxygen (not particles of oxygen).

'Fuels are made of molecules. The atoms [sic] that make up these molecules react with oxygen [sic]. The new molecules made in the chemical change contain less stored energy than the fuel molecules. This is because [sic] some energy is released.'⁴⁷

Despite the encouraging attempt to give a scientifically valid rationale for the reaction occurring, the final sentence manages to reverse cause and effect, suggesting that the release of energy causes the products to be at a lower energy level than the reactants. The release of energy is actually a consequence of this difference in energy levels.

The example of ionic bonding

In Chapter 1 the octet framework was used as an example of a common alternative conceptual framework found among secondary school and college students. At that point it may have seemed inexplicable that so many students should build up a similar set of invalid ideas about central aspects of chemistry. Yet it is clear that many of the statements and diagrams in students' textbooks encourage learners to think in terms of chemical reactions which occur between unbound atoms that are actively seeking to fill their shells by forming chemical bonds. This alternative conceptual framework is surely an example of a pedagogic learning impediment (Chapter 4) – something that largely derives from the way the subject is taught.

Before moving on, it is useful to illustrate this point with the more specific example of the molecular framework for understanding ionic bonding (see Chapter 8) which may be considered to form a part of the wider octet framework. It has been found that students commonly equate ionic bonding with electron transfer between atoms to form ions: the bond is considered to only exist between the particular ions formed by specific electron-transfer events, so in sodium chloride each ion is only bonded to one other, and the resulting ion-pairs are seen as having molecule-like status (see Figure 8.2).

Students' common alternative conceptions of ionic bonding can be found to be well represented in some books. One book examined even presented a diagram which 'shows the molecules [sic] in seawater'. The diagram showed five molecules of water mixed with five 'molecules' of sodium chloride NaCl.⁴⁸ Perhaps at such an incredibly high concentration (about three parts salt to one part water, by mass!) the ions would associate, but this is certainly not a reasonable image of the particles present in seawater.

Another book suggests that 'salt is made from [sic] the elements sodium and chlorine. There is one atom of sodium and one atom of chlorine.'⁴⁹ In this short extract there is an implication that the salt that students will be familiar with from the dinner table would have been manufactured from the elements, and then a transition from the macroscopic level to the molecular level, where reference is made to single atoms, implying the elements are atomic. On the following page a diagram of a 'salt molecule' shows one smiling sodium atom holding hands with one frowning chlorine atom.⁵⁰

Another books reports how

'It is unlikely that a single sodium ion and a single chloride ion would ever find themselves alone together! But it is possible, and this would be the smallest part of the compound which still has the properties of sodium chloride.'⁵¹

Clearly, most of the properties of sodium chloride would not be shared by a single ion-pair. The formation of an ionic compound (such as silver chloride, see Chapter 9) does not require electron transfer. Yet books for students make statements about 'the two basic principles underlying the formation of bonds: electron transfer and electron sharing'.⁵²

Diagrams that purport to be showing 'the reaction between lithium and fluorine' or 'the formation of ionic bonds in sodium chloride, magnesium oxide and calcium chloride', or 'bonding in calcium fluoride' actually show electron transfer between isolated atoms.^{53,54,55} Indeed these electron transfer diagrams are virtually ubiquitous in student texts, and (as in the case of reactions to form covalent compounds) atoms are usually drawn even when one or more molecule's worth of atoms are needed.^{56,57,58,59,60,61,62,63} It has been found that even trainee chemistry teachers find the molecular model of ionic bonding as acceptable.⁶⁴ This can be understood if they are preparing their classes with many of the current textbooks, and it would not be surprising if they actually go on to teach these erroneous ideas. (Perhaps some of them will one day write student texts that perpetrate myths such as the assumption of initial atomicity, and the full shells explanatory principle!)

Periodicals such as *Education in Chemistry* and *School Science Review* often receive letters from readers disagreeing with the interpretations of science put forward by authors of articles (who are often also teachers). For example, the following extract is from a letter objecting to an article in the *School Science Review* which had criticised the notion of sodium chloride molecules. Seeing ion-pairs seen as molecules is a common alternative conception found among students (see Chapters 7 and 8), but the following view point was expressed (some years ago) by a teacher:

'Is it so wrong to refer to a sodium chloride molecule? In the crystal, every sodium ion can be paired off with a neighbouring chloride ion, even though the bonding forces holding them together may be electrostatic rather than covalent. Even in a solution the ratio of the numbers of the two ions is still 1:1, and thus even these we can think of NaCl as a sort of basic unit.'⁶⁵

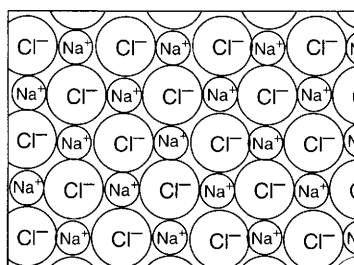


Figure 10.3 Solid sodium chloride

The comment that 'in the crystal, every sodium ion can be paired off with a neighbouring chloride ion' reflects research findings that students will, when shown a diagram such as Figure 10.3, tell the interviewer which (single) cation is bonded to which (single) anion. The ions can be 'paired off' – see Figure 10.4 – but this does not relate to the actual interactions in the lattice, nor to the properties exhibited by the ionic crystal!

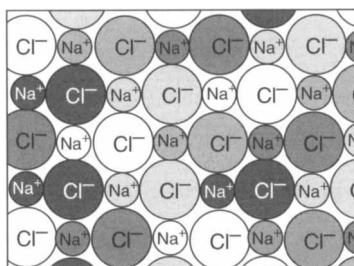


Figure 10.4 The way students sometimes conceptualise sodium chloride NaCl

When the same teacher commented that 'even in a solution the ratio of the numbers of the two ions is still 1:1, and thus even these we can think of NaCl as a sort of basic unit' he was making a valid point about stoichiometry, and perhaps implied the term 'basic unit' in the sense of the empirical formula. However, many students mean something rather different by references to NaCl molecules. It is important that students realise that the main species present in such solutions are the water

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molecules, and the hydrated ions (see Figure 10.5) and not – as many think – ionic molecules (see Chapter 8).

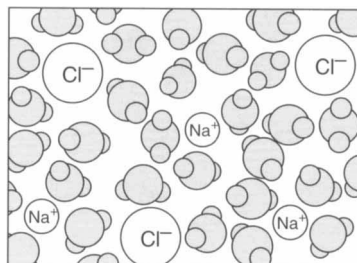


Figure 10.5 Sodium chloride solution

One major concern is when science teachers are teaching outside of their subject specialism. There are non-specialist guides which are designed to help non-chemists plan the teaching of chemistry topics, and these can sometimes be very useful.⁶⁶

However, even these teachers' guides may contain errors. It was pointed out in Chapter 8 that students commonly associate ionic bonding with electron-transfer, which can encourage the development of major alternative conceptions. Yet one guide to teaching secondary chemistry advises teachers that:

'The essential idea for pupils to appreciate is that in ionic bonding metals transfer electrons to the non-metals such that the nearest noble-gas electronic structure is obtained for both the metal and the non-metal ... Appropriate pictorial representations are crucial in this regard.'⁶⁷

The type of representations referred to are the very type of diagram (of electron transfer between isolated atoms) that research has suggested are so inappropriate (see Chapter 8, Table 8.2). The author's figure supposedly showing 'the formation of sodium chloride, shown in terms of the particles involved' has virtually no relevance to any likely chemical process for forming sodium chloride. However, examination questions are regularly set asking students to draw such figures.

Problems of changing conceptions: challenging versus developing students' ideas

Some alternative conceptions are readily overcome, but others are more tenacious. In Chapter 1 it was suggested that it is useful to distinguish between discrete alternative conceptions and alternative frameworks. An alternative framework is a coherent and integrated set of conceptions, some (but not necessarily all) of which are 'alternative' to scientific ideas. Because the ideas are connected, they are mutually supporting: the veracity of any one conception seems to be assured by its relationship to the whole structure. Our conceptual frameworks are judged (usually subconsciously) by their 'explanatory coherence'.⁶⁸ Sets of ideas that seem to fit and have generally worked well together are likely to be retained. Even a few 'shaky' conceptions may be considered acceptable in the context of a generally successful explanatory framework – at least until something with greater overall coherence is available. Perhaps this explains why some experienced teachers writing textbooks seem to adhere to the octet framework in their explanations. Perhaps these authors do think of chemical reactions in terms of atoms trying to fill their shells by sharing or transferring electrons!

Teachers can often find that despite offering students scientifically better ways of looking at a phenomena, the students soon revert to their prior alternative conceptions. This can be disappointing, as one of the teachers piloting materials included in the companion volume reported,

'I found the questions and the students' responses interesting. Even from a superficial glance at their answers, it is clear that the complete shell of electrons dominates their thinking. We have spent some time looking at stability in terms of energy changes and forces between charged particles, so it shows me how easily people revert to simple and familiar ideas.'

A teacher may be proposing to help the student construct knowledge which is more scientific than existing conceptions, but if this means whole-scale demolition of familiar conceptual frameworks the student may tacitly deny the teacher ‘planning permission’.

If learning can only take place in small steps, building on existing knowledge, and yet some alternative conceptions are protected by being integrated into self-supporting frameworks, then bringing about major conceptual restructuring may seem an unlikely target. In practice ‘conceptual revolutions’ do occur – as evidenced by the shifts in perception brought about by scientists such as Newton, Darwin, Einstein, Meitner and Lavoisier. Few students are likely to match the feats of such great scientists unaided, they need teachers to help scaffold their learning (see Chapter 5).

Lavoisier was astute enough to recognise where the existing conceptual structure of chemistry was challenged by anomalous data. He was able to explore a new set of ideas and interpretations, and compare them with the (then) current phlogiston theory. He was able to construct a new framework for chemistry that he ultimately realised explained the facts better. Students can be taken through a similar process.

Eliciting students’ ideas is not an end in itself, but is the precursor to finding ways to demonstrate where those ideas are inadequate (through class practical work, demonstrations, calculations, thought experiments *etc*), and ‘planting the seeds’ of doubt.^{69,70} Some of the classroom materials in the companion volume provide opportunities for students to become aware that their alternative conceptions do not match the facts. The intellectual dissatisfaction or ‘cognitive dissonance’⁷¹ or ‘dis-equilibrium’⁷² produced may well motivate students to find more satisfactory explanations – but the teacher should always remember that the student’s judgement of what is satisfactory is made from the context of their wider conceptual frameworks, and not from the perspective of the teacher’s knowledge base. It may take months, or even longer, for students to give up particularly well established and integrated frameworks. In time, these shifts can be brought about, as the example of a shifting conceptual profile in Chapter 8 (see Figure 8.20) demonstrates – but it may be a slow process. Clearly the teacher has to keep reinforcing the scientific view whenever suitable contexts arise.

Another theme that arises from the ideas discussed in this publication is the way that learning is an active process – that is, it requires activity on behalf of the learner and not just the teacher. This is needed at all levels of the educational system.^{73,74} Students need to be able to explore and play with ideas. The key type of activity is mental,⁷⁵ and with some classes a great deal of active processing of ideas can occur with students sitting quietly in their seats, and the teacher scaffolding learning through a form of Socratic dialogue (promoting independent reflection and critical thinking). Teaching materials which use DARTs and provide scaffolding PLANKs and POLES will help ensure students are thinking, and not just copying notes for rote learning (see Chapter 5). However, with younger students in particular, the constructivist classroom can be a busy place, with students developing arguments and tests for their various ideas, and the teacher perhaps ceding more control than feels comfortable.⁷⁶

It is sometimes implied that there is a tension between two ‘opposing’ views about responding to students’ alternative conceptions. Learners’ ideas may be seen as obstacles to be demolished and overcome, or as the conceptual resources that need to be developed to become more scientific. In practice deeply held conceptions are probably never completely ‘forgotten’ and so a simple substitution model of conceptual change is naive. Conversely ‘development’ must involve persuading students to build new conceptual frameworks which are organised differently, have some different components, and which ultimately will be used in place of the existing ideas. The ‘challenge’ versus ‘develop’ dichotomy is an artificial one. The building process can only use the foundations available, but ultimately looks to change students’ minds.

Planning to avoid learning impediments

One of the themes met in previous chapters is the need to plan teaching so that students are introduced to ideas in a logical way that helps them construct knowledge. There are two main aspects to this planning. One involves analysing the content itself, to make sure that key concepts are

introduced and understood before more complex ideas that build upon them. The second aspect is not to make undue assumptions about students’ existing ideas.

Learning from pedagogic learning impediments

The purpose of labelling some ideas learners bring to class as pedagogic learning impediments is to remind us that if teaching has contributed to their development, we should be able to avoid them in future by changing our teaching. For example, it is known (see Chapter 7 and 8) that many students:

- conceptualise ionic bonding in molecular terms;
- conceptualise metallic bonding as covalent and/or ionic;
- conceptualise giant covalent structures as consisting of discrete atoms or small molecules.

This can clearly be understood in terms of the order in which presentations are made. Usually covalent bonding in simple molecules is studied first, where valency determines bond number, and small discrete molecules are formed. When ionic bonding is discussed the student uses the prior knowledge of the covalent case to make sense of the new learning: so electrovalency is seen as determining the number of bonds formed, and ion-pairs are seen as molecules. (This is of course much more likely to occur when ionic bonding is incorrectly shown as electron transfer between isolated atoms!) The student now has two ‘mental slots’ (see Chapter 9) for bonding, and when metallic bonding is encountered it is often seen in terms of being covalent or ionic. Giant covalent structures are also seen as molecular (and intermolecular bonding in simple molecular lattices is often ignored).

A consideration of students’ ideas such as these, and an analysis of the relative complexity of the different types of structure (see Chapter 3) leads to the suggestion that students are less likely to develop common alternative conceptions if the teaching order was changed. The following teaching order (see Table 10.1) suggests starting with the simplest case, and moving to more complex structures. According to this view, the ‘simple covalent’ case is actually the most complex, because it needs two types of bonding to explain structural integrity, and so it should be taught last.

Type of structure	Bonding	Comments
1. Metallic crystal	Metallic: cations (atomic cores) and delocalised electrons	One element present; charge on cation related to valency
2. Ionic crystal	Ionic: cations and anions	Added complication: two (or more) elements; stoichiometry determined by charge ratios
3. Giant covalent	Covalent	Added complications: number of bonds (and stoichiometry, if a compound) determined by valency; bonds have specific directions
4. Simple covalent	Covalent intramolecular, plus intermolecular (van der Waals, H-bond)	Added complication: additional level of structure – need to consider discrete molecules, and arrangement of molecules in crystal.

Table 10.1 A teaching order for solid structures⁷⁷

Vignette 2: Never assume...

The planning of teaching needs to allow for students' prior knowledge, but as has been shown throughout this publication this cannot be assumed to simply reflect the topics previously covered. Good advice to teachers is to always check prior learning, and not to make assumptions:

- Do not assume that learners have an understanding of previous topics which matches the curriculum version of the science;
- Do not assume that learners have no relevant ideas about topics which they have not previously been taught.

Experience suggests that one can add

- Do not assume the students will already have covered something in another subject.

In Chapter 8 it was suggested that by the time most students complete their secondary education they will have specifically learnt about two types of chemical bonding (ionic and covalent). When they meet chemical bonds, and try to make sense of them, they will do so in terms of this available background knowledge. If a student sees a reference to a hydrogen bond, with no further explanation, it is likely to be interpreted within the existing conceptual framework. The student has the two mental 'slots' (see Chapter 9) for making sense of bonds, and hydrogen bonds (involving hydrogen and another non-metal, usually represented by lines, no charges shown) are likely to be fitted neatly into the slot for covalent bonds.

For example, one post-16 student, Paminder, used the construct 'hydrogen bonding present' when she was undertaking an exercise discriminating between pictures of chemical systems (Kelly's triads – see Chapter 2). This was unexpected as she had not been taught about hydrogen bonds in chemistry at that stage of her course. She suggested that hydrogen bonds were present in a methane (CH_4) molecule. Paminder had acquired the category of hydrogen bond, but had subsumed it within her existing category of covalent bonds. She later explained how she had been introduced to hydrogen bonding in biology,

'at the moment we're doing like about DNA and double helixes, and DNA consists of like bases, of three things actually ... But they've got bases, and they're joined by hydrogen bonding. But the hydrogen bonds are actually holding two bases together.'

However, when asked to explain what hydrogen bonding was she simply described a covalent bond involving hydrogen,

'say for example hydrogen gas, that consists of two atoms of hydrogen, and when they bond they, each one has one electron in its outermost shell, and when they bond, they bond like covalently. And that's what hydrogen bonding is. That's an example of hydrogen bonding.'

Perhaps Paminder's biology teacher incorrectly assumed that she would already have been taught about the concept of hydrogen bonds in her chemistry classes. One of the key messages of this publication is that teachers need to check students' prior learning. As the colloquial spelling *aide-mémoire* suggests: 'never assume – it makes an ass of 'U' and me'.

It seems unlikely that Paminder's case is unique. A recently published text for post-16 biology introduces the term 'hydrogen bonding' without explanation.⁷⁸ An accompanying diagram shows hydrogen bonds in two protein structures. In a schematic representation of the α -helix the hydrogen bond is shown as a dashed line between two parts of the structure. (In the second schematic, for the β -pleated sheet structure, the label for the hydrogen bond appears to be incorrectly pointing to what is presumably an amino acid residue.) A student meeting hydrogen bonding in this context is given no information to help make the learning meaningful. It is hardly surprising therefore that many just assume the hydrogen bond is a bond involving hydrogen. It seems reasonable for the learner to expect that if hydrogen bonding was a new and significant class of bonding, then this would be explained when first introduced.

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As most students enter post-16 courses with a strong commitment to the ‘full shell explanatory principle’ (see Chapter 8), *ie* erroneously believing that bonds form so that atoms may attain octet structures of full shells, the introduction of a new class of bonding that cannot be construed in these terms calls for careful exposition. If biology teachers take their lead from texts which just assume a knowledge of hydrogen bonding then there are likely to be many Paminders in post-16 classes who have formed the alternative conception that hydrogen bonding is a covalent bond to hydrogen, before anyone tries to explain the concept to them.

Making the unfamiliar familiar

Teaching can be seen as being about making the unfamiliar familiar. The obvious way to help a student become familiar with Beethoven’s fifth symphony would be to play it to them, and the obvious way to get students familiar with paper chromatography would be to get them to try it for themselves. However direct experience is not really possible when the unfamiliar is the concept of oxidation numbers, or spin-pairing, or d-level splitting.

One technique commonly used by teachers is to use metaphor or analogy. These are ways of comparing the unfamiliar with something that is familiar, and so make it seem familiar itself. Metaphor is a key aspect of language: indeed it has been suggested that most of our language has derived from metaphor. So we have stories that are deep and those that are tall. People are stars and peaches. Many of our metaphors are ‘dead’. This means that with repeated use they have become accepted as literal meaning (and a ‘dead metaphor’ is an example of a metaphor – the metaphor was never alive!) So we have long pauses – where a word used to describe a length is now accepted as describing the ‘length’ (duration) of a period of time.

It is important to remember that metaphors have ‘hidden meaning’. When we say that there was a pregnant pause, we expect the listener to understand that a pause (however ‘long’) is not literally pregnant, but may be compared with a pregnancy in some way. Metaphorical language is poetic, and relies on the listener (or reader) to interpret the hidden meaning. When the reader is sophisticated, then metaphor can be very effective. A number of metaphors have been used in the text of this publication. The notion of a learning-doctor; references to conceptual structure as a substrate, to which anchors need to hook; to conceptual flotsam and jetsam; to icebergs of knowledge, and to ‘gaps’ in knowledge; to mental slots (and concept maps); to raw material for building learning (when planning permission is granted); and to seeds of doubt. Part of the rhetorical ‘force’ of such metaphors seems to derive from the very way that they are ‘planted’ in the text without explicit explanation.

However, metaphor may not be so effective when used with students who may lack sophisticated language skills, and who may expect teaching to be more literal. For example, social metaphors are often used to introduce students to the unfamiliar world of the chemist’s molecular models. Sometimes this is done in quite unsubtle ways,

‘The combining power of each atom is its valency. Think of the valency as the number of hands that each atom has to hold on to another atom.’⁷⁹

Students seem to take to this notion of atoms as being like social beings, who enter into various relationships with other atoms. This helps them get an image of the molecular world, but sometimes they may have difficulty moving on beyond this stage.⁸⁰ For many students the atoms are actively trying to get full shells. If students are satisfied with this level of explanation, then there is no intellectual motivation to learn a more abstract explanation.

Using analogies to anchor to the conceptual bedrock

A main disadvantage of using a metaphor in teaching, is that it has ‘hidden meaning’ which needs to be ‘unpacked’ by the reader or listener. Similes are more suitable, as there is an explicit effort to make a comparison between the unfamiliar and existing knowledge. However, even when such a reference is made, it is necessary to spend time to make sure the comparison is explored. Consider an example from a student textbook, introducing the idea of atoms. An initial statement that ‘Scientists have

studied the behaviour of atoms since 400 BC...' seems rather dubious: certainly CERN has not been around quite that long. The book goes on to ask students to make the comparison between atoms, and bricks and stones. The notion of 'atoms as building blocks of matter' was criticised in Chapter 6, but putting such concerns in abeyance, consider how helpful the following extract is to the student just learning about atoms:

'There are about 112 different kinds of atoms. Each one kind is a separate element. [Note the invalid transition from the molecular level to the macroscopic] ...How can these tiny atoms be different? It helps to think of stones or bricks. Bricks do the same job (they join with others to make the wall), and they are made of the same kinds of substances. However, you can mix the ingredients in different ways and amounts to make different kinds of brick. Put these together and you get different kinds of walls.'⁸¹

Are the bricks meant to be the atoms, or the sub-atomic particles that make up the atoms and so make them different? Do bricks do the same job as atoms, or as stones? Are bricks made of the same kinds of substances as atoms, as stones or as one another?

I find myself at a loss to understand exactly what is being compared with what in this explanation. I find it even harder to see what a student is meant to make of this. It is no wonder that students learn ideas in science uncritically ('reactions occur for atoms to get full shells', see Chapter 9), when even attempts to make the unfamiliar familiar can be so confusing. One key point in using analogies is to be explicit about how they map onto the target concept.

Vignette 3: 'The MCG analogy is analogous to the Yankee Stadium analogy'...

In a fascinating paper about a students' learning about key chemical concepts there is a reference to a Melbourne Cricket Ground (MCG) analogy that was 'used in class' when teaching about the atom.⁸² As the authors were reporting work undertaken in Australia it is likely that a comparison between an atom and the MCG would make sense to the students in the class. Presumably the size of the nucleus in an atom was being compared with a relatively small object (a cricket ball) placed in the middle of the MCG.

The paper was published in an international journal, based in the USA, and a note had been added to the end of the paragraph to explain that 'the MCG analogy is analogous to the Yankee Stadium analogy...'. One of the authors decided that the MCG example was too obscure for readers in some countries, and that the analogous analogy (presumably of a baseball at the centre of the Yankee stadium) would be more familiar. So here we have an example of an analogy made between two analogies. The original analogy between an atom and the Australian sports context was judged inaccessible to some readers, and so a further analogy was drawn.

For someone teaching in the UK the baseball example would not be particularly familiar to many students, and a better example might be from association football. For UK teachers, then, the journal perhaps could have explained that:

'The MCG analogy is analogous to the Yankee Stadium analogy [which is analogous to the Wembley Stadium analogy].'

Target	Nucleus	Atom
Analogy for Australian context	Cricket ball	Melbourne Cricket Ground
Analogy for USA context	Baseball	Yankee Stadium
Analogy for UK context	Soccer ball	Wembley Stadium

Table 10.2 An analogous set of analogies

In other words, the reference to the Yankee Stadium was introduced to help the reader who was not familiar with the MCG: but for many readers in the UK, NZ, the Indian subcontinent, the West Indies and southern Africa, the baseball example would be less familiar than the original cricket reference. This is not intended as a criticism of the authors' selection of examples, but just a useful reminder that our judgements of what is and is not familiar to others can sometimes be mistaken.

In Chapter 7 the analogy between the atom and a solar system was considered. It was suggested there that this analogy derives from an assumption that students will be familiar with the structure of the solar system, and can use this knowledge to form an initial image of the atom. As was reported in Chapter 7, the assumption that learners are better informed about the solar system than the atom may not always be justified. Not only do analogies have to be explicitly mapped, they also have to be selected so that the analogue is genuinely familiar to the students.

Vignette 4: The parable of the molecular scissors

'Enzymes are biological scissors cutting up large molecules and making them into smaller more manageable pieces.'⁸³

So part of the craft of the teacher consists of making the unfamiliar familiar by making comparisons with what is already known. Teachers therefore need to have the imagination to be able to think up useful analogies. The analogy will only be useful when the connection between analogue and target is clear, and when the analogue is genuinely more familiar than the target concept. A student who has seen the 'kick-off' of a football match from the perimeter of a large stadium will be able to draw upon that knowledge to see how the nucleus is very small in comparison to an atom.

The textbook example about comparing atoms and bricks demonstrates how the comparison needs to be explicit. The example of the atom-as-a-tiny-solar-system (see Chapter 7) reminds us that students are not always as knowledgeable about the analogue as teachers may expect. Once again, the lesson here is not to assume, but to check, that students do appreciate the aspects of the analogue being referred to. Not only do analogies have to be explicit, they also have to be selected so that the analogue is genuinely familiar to the students.

Selecting a suitable and familiar analogue is only part of the process of making the unfamiliar familiar. If students are to benefit from the comparison they should be asked to focus on both the aspects of the analogy where the analogue maps onto the target, and those where it does not. Perhaps in the Wembley Stadium example it would be clear that only the idea of relative scale is relevant. However, in the comparison between the atom and the solar system there are a number of significant differences, such as the way electrons (unlike planets) repel each other, or the way the solar system (unlike an atom) is almost planar.

This can be well illustrated by an example of a teaching analogy in use. I was observing a lesson being taught by a student teacher. He was an intelligent, enthusiastic trainee, and had prepared his lesson well. He was teaching a class of 14–15 year olds about enzymes. Large molecules to be digested had been modelled as a string of beads, which could not pass through the gut wall until the string had been broken. At one point an analogy was made between the enzyme and a pair of scissors. At this point I made a comment in my observation notes:

'In what ways is/isn't the lipase like a pair of scissors? A useful analogy – but how far can it be pushed?'

The analogy has the potential to be fruitful. As was pointed out in Chapter 6 many students find the (unfamiliar) molecular world difficult to understand. The notion of the enzyme having a role like scissors cutting through the string of beads is a potentially useful comparison. The students would all have experience of cutting things up with scissors, and were likely to be able to form a relevant mental image of the function of the enzyme.

However, what was lacking was a discussion of how far this analogy could usefully be taken. Clearly the mode of action of the enzyme molecule was very different to that of scissors. Although students at this level would not be expected to appreciate the detailed mechanism of enzyme action, they should

appreciate that the process relies only on the shapes of the molecules involved. Scissors, of course, rely on two key physical principles – the concentration of force due to having sharp blades, and the presence of a pivot to allow leverage. In other words, a pair of scissors only works because an external agent (a) positions the scissors over the object to be cut; and (b) applies a force in the required direction. The action of an enzyme does not require any such external agent.

This particular class were set the task of producing a summary of their learning about enzymes. Perhaps unsurprisingly the idea of the molecular scissors was included in a number of the pieces of work. What was slightly more unexpected was the way that a number of the students drew diagrams showing molecule-sized scissors cutting up the long chain molecules (eg see Figure 10.6).

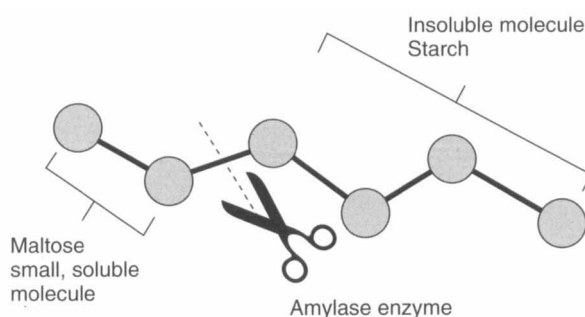


Figure 10.6 A student's diagram showing enzyme action (redrawn)

It would seem that for these students the enzyme was not a molecule which functioned like scissors so much as a molecule-sized pair of scissors. Some learning had taken place, but the task of constructing a scientific understanding was only just beginning (see Figure 10.7).

Developing a constructivist approach (summary)

Meaningful learning requires students' active participation in problem-solving and critical thinking about activities which they find relevant and engaging. They are 'constructing' their own knowledge by testing ideas and approaches based on their prior learning and experience, applying these to a new situation, and so relating the new knowledge gained to their existing conceptual frameworks.

Constructivist science teaching takes into account what we have discovered about how learning occurs. Teaching sequences should be designed that begin by eliciting the students' current ideas about a subject. This process may sometimes be carried out by the teacher's verbal questioning; or by asking students to produce concept maps, to brain-storm posters for a topic in small groups, to discuss concept cartoons, or by using a written probe as a pre-test.

Teaching can be better planned when students' alternative conceptions can be anticipated, in order to take their ideas into account. Active exploration of the limitations of students' existing thinking is often necessary to move students towards the accepted scientific view.

The design of the teaching sequence should not derive only from the content to be covered, or the standard experiments traditionally performed. Rather planning needs to be based upon an analysis of the conceptual structure that it is hoped that the students will acquire, in relation to their current understanding. This will determine the logical sequence most appropriate for learning, and this may not match the historical development or standard textbook presentations. The students should be asked to use their existing knowledge to formulate ideas which can then be challenged by being tested for internal coherence, and for consistency with both experiment and related areas of knowledge. Clearly hypothesising, predicting, and critical discussion form an important part of this process.

The constructivist chemistry teacher is both a classroom researcher and a learning-doctor. Responding to student misconceptions effectively requires teaching that is honed to the needs of each group of learners, and is an interactive process that is both challenging and stimulating: much like science itself.

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