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9. Chemical reactions

The study of reactions is at the core of chemistry as a subject. This chapter considers areas where students are known to have difficulties in learning about reactions in chemistry. It also introduces some of the classroom exercises included in the companion volume to help teachers elicit and challenge their students alternative conceptions.

Describing chemical reactions

The main defining characteristic of a chemical reaction[1] is that it is a process where one or more new substances are formed, *ie*:

reactants → products

Here the reactants and products are different chemical substances.[2,3] The basic way of describing chemical reactions, then, is to write 'chemical equations' showing the reactants and products in a particular chemical change. Chemical equations have been described as 'an essential part of the common language of scientists'.[4]

Chemical 'equations' are commonly written as word equations and formulae equations. There is a sense in which formulae equations are easier, as they provide a ready means of checking that no transmutation has been implied (by seeing that the same elements are represented on both sides of the equation). However, formulae equations are more abstract, and so word equations are often introduced first.[5]

Word equations relate to the macroscopic level of laboratory phenomena that may be directly experienced by students, whereas formulae equations are directly related to the molecular level (see Chapter 6). The full implications of formulae equations can only be appreciated by a student who has been introduced to the molecular and/or ionic nature of the reacting substances.[6]

Although word equations use the (often) less abstract names of substances, rather than formulae, they can make it more difficult for students to check that the same elements are represented before and after a reaction. Students need to know, for example, that the ending '-ate' implies the presence of oxygen, and which elements are present in common substances such as water or ammonia.

Student difficulties with word equations

Word equations are commonly introduced and used in lower secondary science, but national testing of students at this age in England and Wales shows that many students find it difficult to write or complete word equations for chemical reactions.[7]

This should not be surprising if it is remembered that although chemical names seem familiar to teachers (with many years of acquaintance using them) they may seem somewhat arbitrary to students. One science educator has told me how in school he spent two years perplexed at why chlorides should be produced in reactions of 'hydraulic' acid! The more systematic names, such as tetraoxosulfate(VI) for the SO_4^{2-} ion, may be especially difficult for students.[8] If the names do not seem to fit an accessible pattern, then students may well be concerned about the very large number of substances they could hear and read about.

Clearly the expert (the teacher) has another advantage in having a well established framework for seeing specific reactions as particular examples of common reaction types. For the teacher, this classification system acts as a set of familiar 'mental pigeon-holes' into which reactions may be slotted. Each of these 'slots' is a ready made set of mental connections for the specific reaction being discussed (see Figures 9.1 & 9.2).

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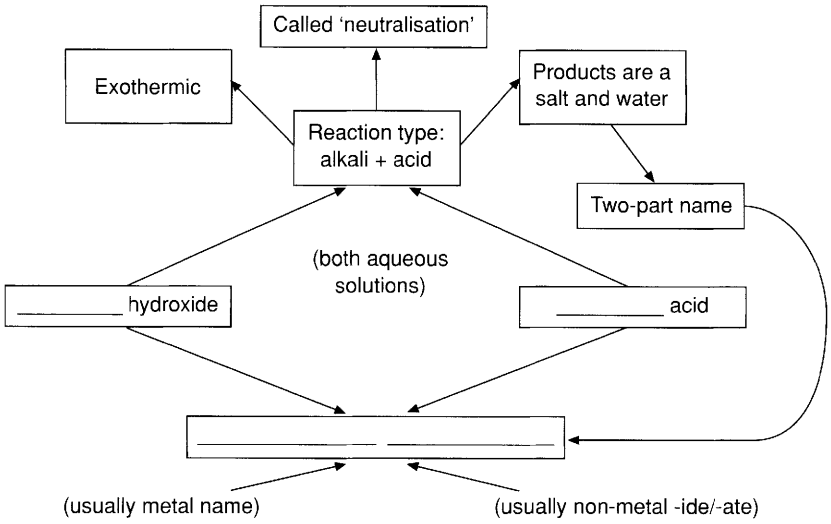

Figure 9.1 A 'mental slot' ready for thinking about a type of reaction

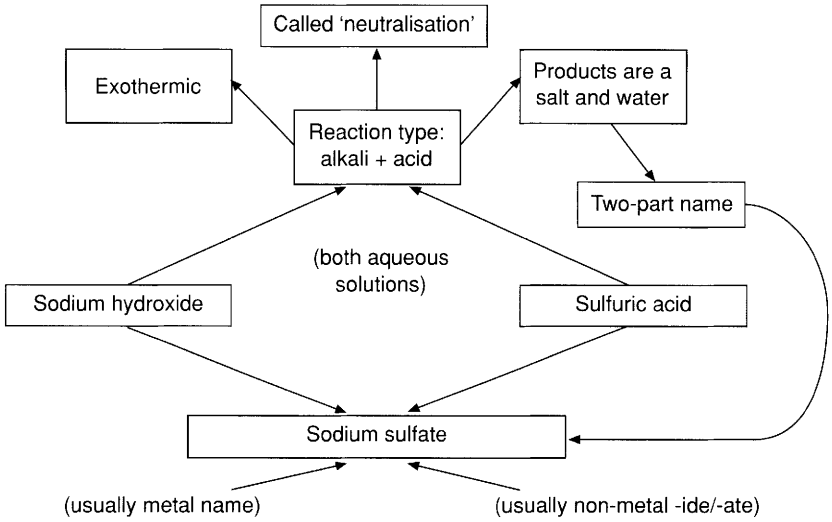

Figure 9.2 A specific example is fitted into the 'mental slot'

Students, lacking this framework for organising the information, see the equations at a much finer resolution – in the terms of Chapter 5 – so that a chemical equation that the teacher perceives as an integral unit seems to the students to have many components. For the expert (the teacher) the equation is easier to hold in mind once it is recognised as fitting a familiar 'slot'. For the novice (the student), lacking the teacher's background, classifying the reaction is itself an additional cognitive demand, which does not automatically bring the benefits that accrue to the expert.

One of the resources included in the companion volume, **Word equations**, is an exercise on completing word equations. This exercise is not designed around teaching students a set of rules, but rather with giving them an opportunity to see that, although there are many possible chemical reactions, those met in school science may often be fitted into a limited number of common types. (The types used in this resource are binary synthesis; displacement of a metal from a salt; neutralisation; acid with carbonate; and acid with metal.)

This approach is designed to help students start constructing the reaction-type mental 'slots' into which they can 'drop' reactions (in the way discussed above).

The teaching exercise is accompanied by two diagnostic assessment probes, which ask students to complete word equations. Whereas the teaching exercise presents the examples within a framework with plenty of cues (to help students work out the answers), the two assessment tasks simply present five incomplete word equations for students to complete. (The teaching exercise may be seen as providing 'scaffolding', in the sense discussed in Chapter 5, a structure within which the students are enabled to complete a task which might otherwise be beyond them.)

When the materials were piloted the two assessment tasks were used as a pre-test and post-test to enable teachers to judge if students had learnt anything by undertaking the teaching exercise. This would be a sensible way of using the materials if they are adopted with a class that should have already covered the material. (Indeed, if the students demonstrate competence on the pre-test, then the exercise and post-test will not be needed).

However, if the materials are used as part of the normal introduction and teaching about word equations then it would be more appropriate to use both of the diagnostic assessment probes as post-tests after the teaching exercise. This could either be as an immediate and a delayed post-test (one used straight after teaching, another some time later when revising the topic), or the first could be used as a 'filter', with only those having difficulties asked to undertake some more work and the second probe.

When these materials were piloted it was found that many students found difficulty in completing simple word equations (something which had been highlighted previously in national testing of 14 year olds in England and Wales, and so had been anticipated). It is worth considering some of the responses to the pre-test, from students in a group of 14–15 year olds.

Perhaps the simplest question was the item based on a binary synthesis. Most students realised that a reaction between calcium and chlorine would produce calcium chloride, although calcium chlorate was also suggested. Similarly, many students were successful on the item based on the displacement of a metal from its salt by a more reactive metal. It was generally recognised that it would need to be copper nitrate (solution) which reacted with zinc to give zinc nitrate (solution) and copper. Even here there was some alternative answers. One student suggested the answer was copper sulfate because 'zinc will displace copper sulfate'. This response seemed to be based on trying to recall the reaction, rather that work out the logic of the equation.

Another student in the class who did try to use the information given produced an incomplete answer of nitrate as 'it says zinc nitrate'. This student did not bring to mind that the question 'also said' copper. However, in general, these two items seemed to be tackled well by the group.

The other three items seemed to place heavier demands on the students. The neutralisation item required students to identify the salt (*ie* potassium nitrate) which would be produced from a particular acid (nitric acid) and a particular alkali (potassium hydroxide). This question produced a range of alternative suggestions from this one teaching group: nitric hydroxide; hydrochloric acid; potassium nitric acid; hydrogen; potassium nitrate acid; nitric oxide; potassium acid; nitric acid. Whilst some of these responses were guesses (as admitted by the students), others were genuine attempts to apply logic based on the information given, and the type of things that happen in chemical reactions,

'nitric acid + potassium hydroxide → potassium nitrate acid + water

[because] when water is taken out of the equation you are left with potassium nitrate acid.'

'nitric acid + potassium hydroxide → potassium acid + water

[because] potassium will displace the nitric acid'

The acid which is reacted with zinc carbonate to produce zinc sulfate, water and carbon dioxide was suggested to be sulfate acid; hydrochloric acid; hydroxide acid; and sulpher [*sic*] hydroxide acid. Again there was some evidence of a logical approach,

'hydroxide acid + zinc carbonate → zinc sulfate + water + carbon dioxide

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[because] when looking at the [equation] I can tell what is missing from either side as it is meant to be equal.'

This student was partially right: yes, it was meant to be 'equal', but, no, he couldn't tell what was missing.

The item based on a metal reacting with an acid also gave a range of responses. When magnesium reacts with hydrochloric acid to produce hydrogen, then the other product expected by various students was water; magnesium hydroxide; magnesium oxide; magnesium – because 'it is magnesium and hydrochloric acid'; and magnesium acid 'because I believe the acid has been given to the magnesiume [*sic*]'.

What this brief examination of the responses of a single group suggests is that while some students are totally at a loss with word equations, others make mistakes despite having a valid strategy. Some of those students who appreciate the basic idea of conservation (*ie* both sides are equal in some sense), and realise that they should be able to work out 'what is missing', still fail because they are not familiar enough with the naming of categories of chemicals (oxide, hydroxide, acid, -ate, -ide, etc) or with the general equations for reactions (the mental pigeon holes discussed above). The demands prove too great for students who can not effortlessly call upon these mental resources. The task is too complex when seen at the resolution available to the student.

Types of reactions

Only a limited number of types of reactions are commonly considered during school science. However, these categories are not mutually exclusive, which may confuse students.

One of the probes included in the companion volume, **Types of chemical reaction**, presents a range of reactions to students, and asks them to classify the reactions in terms of five specific categories and a 'none of the above' option. The examples chosen are intended to be those that students are likely to meet in their courses, and are described in both word and formulae equations. The students are also asked to explain their choices, so that they will think about their own reasons for making the classifications. Some students will find this quite difficult, but this 'metacognition' - thinking about thinking (see Chapter 3) - may be useful when asking students to revisit any question that have classified incorrectly. It may also help teachers to spot why students are making mistakes – a key aspect of diagnostic assessment (see Chapter 10).

The categories used are displacement, neutralisation, oxidation, reduction and thermal decomposition. The decision to give separate categories for oxidation and reduction, rather than a 'redox' category, was based upon the way these concepts are often introduced (in terms of addition and loss of oxygen and hydrogen). Clearly, when the idea of redox is taught, it becomes an appropriate teaching point that whenever a reaction is classified as an oxidation it must also be a reduction, and vice versa.

When this probe was piloted, it was found that students had considerable difficulty in classifying reactions. One aspect that clearly troubled some students was that the same reaction might be an example of several categories of reaction.

For example, the first question asks about the reaction between nitrogen and hydrogen to produce ammonia. This is a redox process, and even students operating with an elementary concept of oxidation and reduction might be expected to consider nitrogen as being reduced (due to the addition of hydrogen). However, a number of students in a class of 15-16 year olds classed this reaction in the 'none of the above' category. The reasons that students gave were often that it fitted some other category that was not on the list. The reaction was described variously as:

- a reversible reaction;
- a simple reaction of two elements;
- requiring heat;

- a normal reaction; and, by contrast,
- an unusual reaction.

One student also put the electrolysis of sodium chloride in the 'none of the above' category because 'it is electrolysis of brine'. It would seem that when some students already had a label for the reaction and found that it was not listed, they did not examine the other categories closely to see if they also applied. This is a particular concern when many reactions may be classed as displacement reactions. For example the reaction between sodium hydroxide and nitric acid was considered to be a displacement (and in no other category) as 'the Na is more forming a new chemical with the nitrate [because] they are more reactive' or because 'they swap around'. Similarly the reaction between copper carbonate and sulfuric acid was also considered to be a displacement 'because the CO_2 has been displaced' and because 'the substances displaced each other'.

Other students thought that this reaction was a neutralisation 'because the sulfuric acid has been neutralised'. Although this is an acid-base reaction, the term neutralisation is usually reserved for acid-alkali reactions. Another student in the group classed the reaction between zinc (a 'base' metal) and hydrochloric acid as a neutralisation.

This was not the only unconventional interpretation of a term. The decomposition of copper carbonate into copper oxide and carbon dioxide was classed as a reduction 'because the copper carbonate has been reduced to form copper oxide and carbon dioxide'. The same individual also classed the electrolysis of sodium chloride in this way 'because the sodium chloride has been reduced to sodium and chlorine'. This would seem to be a sensible application of the everyday 'life-world' meaning of 'reduced' (see Chapter 2).

The combustion of methane was classified in two different ways.[9,10,11] Some students saw this as a displacement reaction as 'oxygen take[s the] place of hydrogen in carbon' (or 'the oxygen displaces the hydrogen'), or, as another student explained, 'they swap around'. Other students saw this reaction as a thermal decomposition. One student pointed out that 'the steam indicates [that] there's heat', and another explained that 'the heat is put into the methane and oxygen then it will form carbon dioxide and steam'. Another classmate made the valid observation that 'the methane has been broken down by heat', but – of course – chemists use the term thermal decomposition in a more restricted sense.

Why do reactions occur?

Explaining 'why' reactions occur is a much more difficult task than either completing equations or classifying reactions. Indeed, this topic is not usually dealt with in any meaningful sense until at post-16 level. In one sense this is understandable, as valid explanations require detailed consideration of bond enthalpies, or – at least – a sophisticated application of notions of electrode potentials and Gibbs free energy. In some cases a qualitative treatment of entropy can be used.

Yet research has suggested that many students believe that they do know why reactions occur by the time they complete their secondary science courses.[12] However, the reasons they commonly give are invalid, and may be in contradiction to ideas that they would be expected to learn if they continue their study of chemistry to post-16 level.

The most common alternative conception is to suggest that chemical reactions occur 'so that atoms can acquire a full outer electron shell' or 'an octet of outer electrons'. Students at the end of secondary schooling, or during post-16 courses, will commonly give a response along these lines, even if the information given in the question clearly shows this cannot be a valid explanation.

One of the resources included in the companion volume, **Hydrogen fluoride**, is a diagnostic probe which enables teachers to explore their students' understanding of why reactions occur. In this diagnostic probe students are told that 'Hydrogen reacts with fluorine to give hydrogen fluoride.' The students are given both the word and formulae equations to consider.

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The equation for this reaction is:

$H_2(g) + F_2(g) \rightarrow 2HF(g)$

The word equation is:

hydrogen + fluorine → hydrogen fluoride

Students are also presented with a diagram (see Figure 9.3).

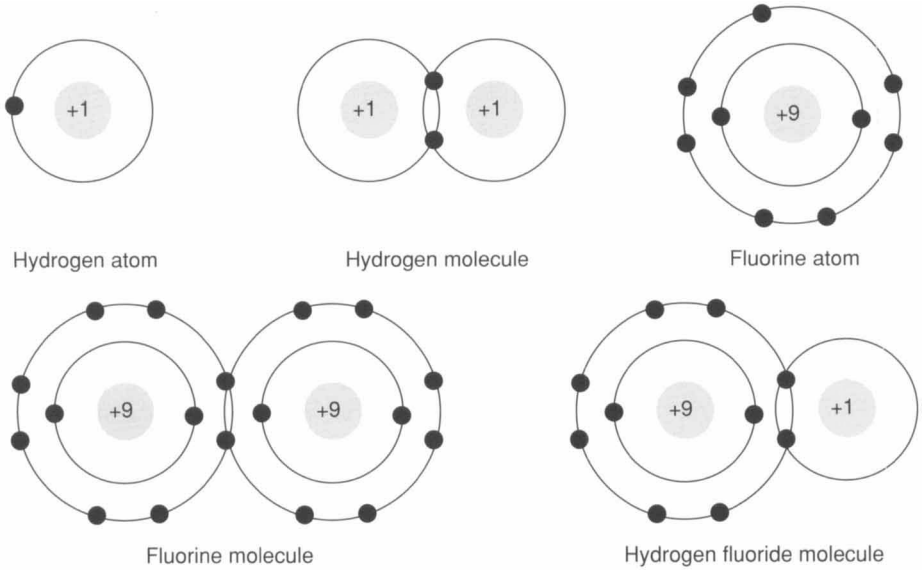

Figure 9.3 Figure used in the Hydrogen fluoride probe

The task students are set is to 'In your own words, explain why you think hydrogen reacts with fluorine'. The figure shows a molecule of each of the reactants, and of the products, and also of the hydrogen atom and the fluorine atom. At the molecular level, the process which needs to be explained is that given in Figure 9.4.

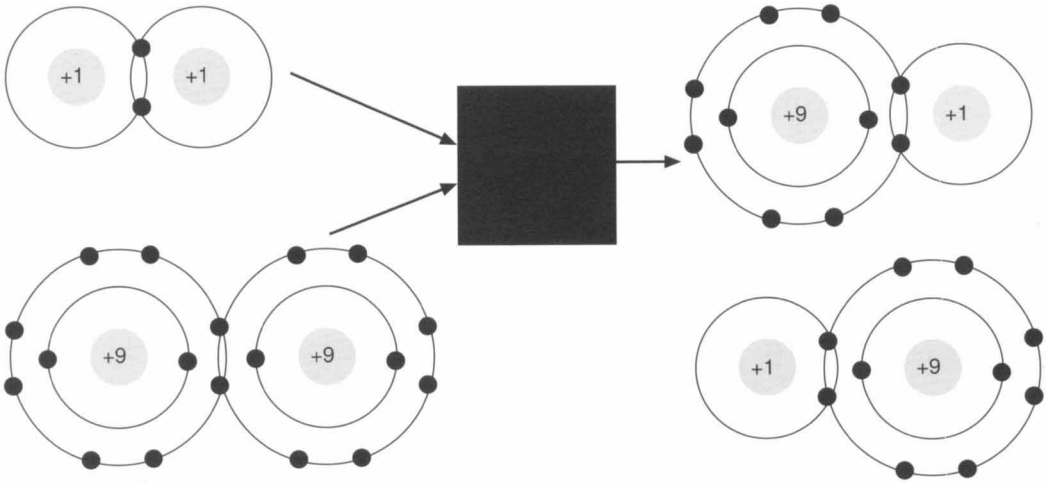

Figure 9.4 The reaction between hydrogen and fluorine

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Both the reactants and products are molecular, and so any explanation that students produce at the molecular level needs to relate to these species (as is implied by the equation showing the reactants as $H_2(g)$ and $F_2(g)$). In this case entropy cannot be used as an explanation.

The figure presented to students also includes the atoms, as these are known to often dominate student thinking (see Chapter 6). Of course, atoms could be involved in the mechanism (in the black box in Figure 9.4), as could a number of other species (see Figure 9.5). However, the reaction process can not be explained in terms of properties of isolated atoms, as the reactants are not present in this form. I have laboured this point, because in many groups it is found that this is how students explain the reaction.

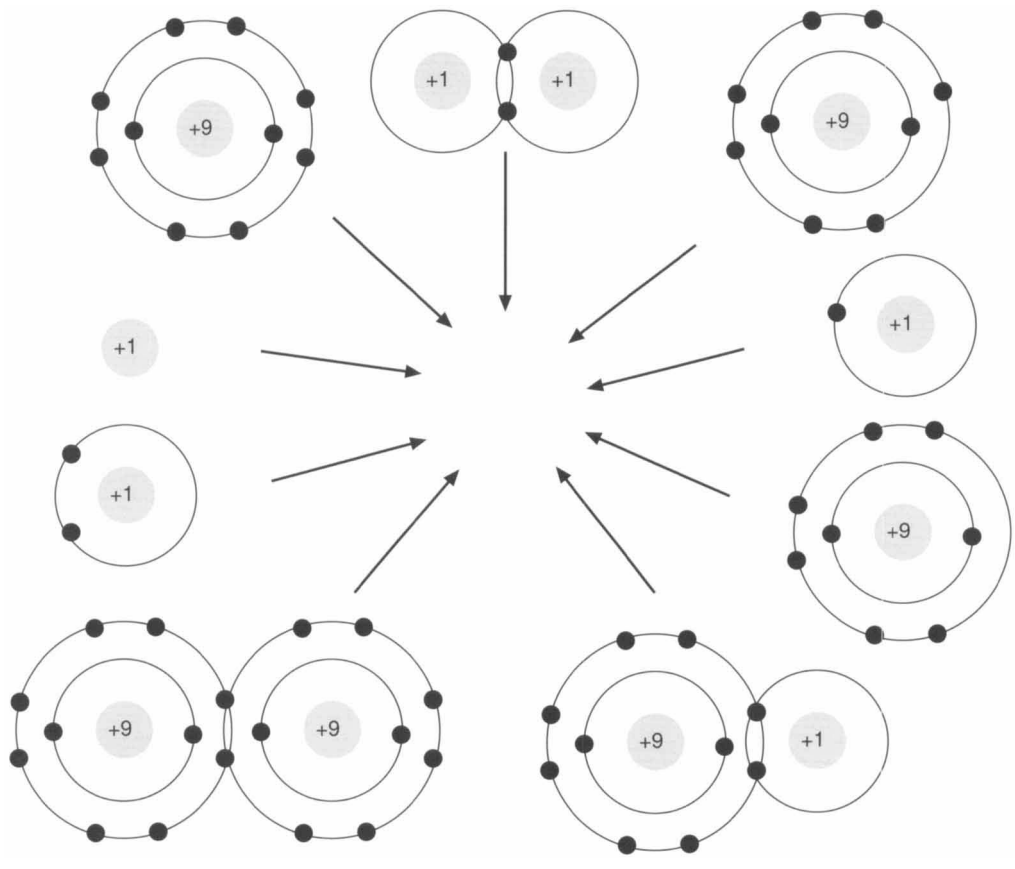

Figure 9.5 Some species that could be present (at least transiently) as hydrogen and fluorine react

When this probe was piloted, it was indeed found that many students explained the reaction in terms of the atoms of hydrogen and fluorine striving for octets of electrons. (See Chapter 8 for a consideration of how students apply the 'full shell explanatory principle' to bonding.)

For example the following response was from a student in a group of 14–15 year olds:

'All atoms have electrons in their outer shells. They want to get a full outer shell. Fluorine atoms need one electron to get a full outer shell, and hydrogen only has one, but needs one more. Therefore, they bond together, the hydrogen electron fills in the gap in the fluorine, and the hydrogen uses one of the fluorine electrons so they both have full shells.'

This was far from an isolated suggestion. The following response was from a student in a group of 15–16 year olds in another school,

'Hydrogen contains only one electron. The first shell of an atom always contains only two electrons at the most, while the other shells following that can contain up to eight electrons each. This means

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that in order to reach a stable state hydrogen needs only to gain an extra electron to have a full outer shell. Fluorine has seven electrons in its outer shell so needs to gain one more too. A hydrogen and a fluorine atom both share an electron each to form a single covalent bond.'

Both of these explanations are clearly from eloquent and thoughtful students. The are both 'logical' explanations, but based on the premise that the reactants are present in the form of atoms. To be fair to these students (and many others in these classes making similar suggestions), the issue of why reactions occur is seldom taught in any depth (if at all) in secondary school, and many student texts do imply that reactions occur to allow atoms to fill their shells (see Chapter 10).

Once students study chemistry in post-16 courses they will study concepts such as bond enthalpy, free energy changes, and reaction profiles. However, even students who have studied these topics may tend to explain the reaction in terms of the 'needs' of discrete atoms. Students in a group of 17–18 year olds gave the following explanations when responding to the probe:

'A fluorine atom has an incomplete outside shell of electrons of only 7, and a hydrogen atom also has an incomplete outside shell of 1....'

'...hydrogen reacts with fluorine as fluorine only has 7 electrons in its outer shell and needs hydrogen's single electron to give it 8 electrons in its outer shell and make it a stable molecule ...'

'Because both atoms need one extra electron in their outside shell to have a noble gas structure, so by sharing 2 electrons (one from each atom) in a covalent bond, hydrogen fluoride becomes a very stable molecule....'

'Hydrogen and fluorine atoms are both uncharged (but unstable) particles with unfilled outer shells of electrons....'

Similar responses to this probe, starting from the electronic configurations of isolated atoms, have been obtained from many students in a range of institutions. This would seem to be a very prevalent and strongly held alternative conception, making up a part of the common 'octet' alternative conceptual framework (see Chapter 1).

How do reactions occur at the molecular level?

Given that the 'full shells' explanatory principle can not be called upon to explain why reactions occur, there is a need to provide students with an alternative explanation.

At post-16 level a thermodynamic approach is often taught. In this the main considerations are the usually the bond enthalpies of the bonds broken and formed in a chemical process. In the example of the reaction between hydrogen and fluorine, bonds are broken in hydrogen (requiring 436 kJ mol^{-1}) and in fluorine (158 kJ mol^{-1}), and formed in hydrogen fluoride (562 kJ mol^{-1}, bearing in mind that 2 moles of HF are produced for each mole of hydrogen(/fluorine) reacting).[13] If there is an increase in disorder than entropy effects can also be considered.

An explanation may therefore be given in terms of the products being more stable, as there are stronger bonds in the product. If students require a mental image, then they can be asked to think about the electrical interactions between nuclei (or atomic cores) and valence electrons when the molecules interact. Those students taking post-16 level courses in physics may be able to think about the molecules quantacting (see Chapter 6) in terms of lowering the electrical potential of the system of charges. However, this is a rather abstract notion, and a deep understanding requires students not only to bring in ideas from physics (which many find difficult – see Chapter 7) but also to bear in mind that quantum theory places restrictions on the allowed configuration of electrons and nuclei.

Nevertheless, it seems sensible to encourage students to think about reactions in terms of the quantaction of the molecules, and the electrical interactions between different reacting species. This will certainly be useful when students are expected to appreciate and explain reaction mechanisms (see below).

Practice in this area may be important, as evidence from research suggests that post-16 level students may often have difficulty visualising molecular level processes that their teachers may think are quite straight forward.

Consider, for example, the case of precipitation (double decomposition) reactions, such as that which forms the basis of the common test for chloride ions:

sodium chloride(aq) + silver nitrate(aq) → sodium nitrate(aq) + silver chloride(s)

The basis of this reaction seems simple. In the two solutions the ions present are all solvated (*ie* hydrated), but when the ions are mixed the silver cations and chloride anions bond together, and precipitate as silver chloride. An explanation of this may be given in terms of the energy involved (released) in solvating the various ions, compared with the energy involved (released) in forming the various possible crystal lattices ($AgNO_3$(s), NaCl(s), AgCl(s), $NaNO_3$(s)). In terms of the 'molecular' level species present, the quantaction process concerns the strong forces of attraction between silver ions and chloride ion bringing them together to the exclusion of the solvating water molecules.

Although, no doubt, some transient clumps of other ion combinations also occur in the melee, the random motion of the water molecules is presumably vigorous enough to break up these groupings – which is why the other three compounds involved ($AgNO_3$, NaCl, $NaNO_3$), unlike silver chloride, are fairly soluble.

However, when post-16 level students have been asked about such reactions, they may describe a very different mental image of the quantaction process – suggesting that the basis of the reaction is silver atoms donating electrons to chlorine atoms to form the ionic bond.

In part this 'explanation' is just one manifestation of the tendency for students to think of reactions in terms of atoms (see the example of the reaction between hydrogen and chlorine, above, and the discussion of the 'atomic ontology' in Chapter 6), and to identify ionic bonding with electron transfer (see Chapter 8). However, this also demonstrates that many students do not have a very clear mental image of the particles present in a solution.

Students' ideas about the mechanism of ionic precipitation

One of the resources included in the companion volume, **Precipitation**, includes a diagnostic probe designed to elicit students' ideas about precipitation reactions. This is based around the example of precipitating silver chloride (see above). The reaction might be summarised as in Figure 9.6.

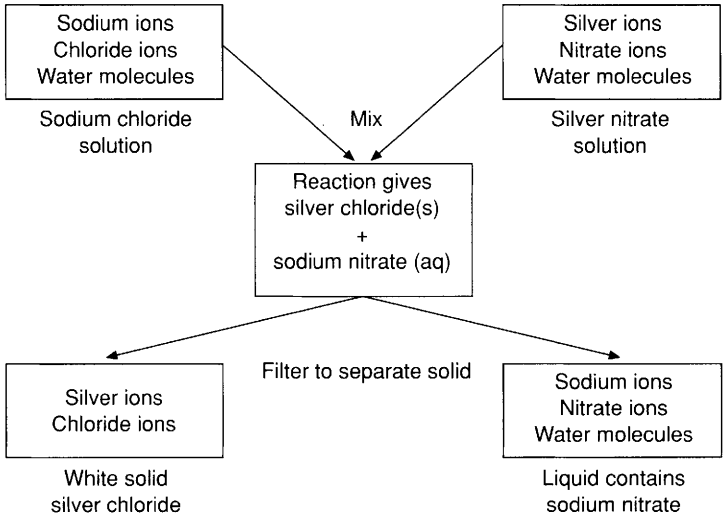

Figure 9.6 The precipitation of silver chloride

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The probe presents students with figures showing the particles in silver nitrate (solid), sodium chloride (solid), water (liquid) and silver chloride (solid). The particles shown in each diagram (specific ions or molecules) are also listed. The probe comprises of a structured question which asks about the particles present when solutions of each of sodium chloride and silver nitrate are formed (see Chapter 6); the particles in the liquid after the reaction (when the solid has been filtered off); and the bond in the precipitate.

When this probe was piloted in schools and colleges it was found that many 14–16 year old students have genuine problems making any real sense of the precipitation process. For example, in one group of 14–15 year olds, the explanations of what happens when the ionic bond forms included:

- 'The ions lose their individual charges and stick to each other.'
- 'The sodium and silver ions have switched places because the sodium ions are more reactive and therefore a displacement reaction will take place.'
- 'The silver will gain an electron and the chloride will lose an electron to become Ag and Cl instead of Ag^+ and Cl^-. They become stable.'
- 'The solid silver chloride is formed and hydrogen is given off along with silver chloride which is a solid.'
- 'The outer electron from the silver transfers into the outer shell of the chlorine. There would be an increase in the number of bonds.'
- 'The silver and chloride ions join together to form one solution.'
- 'They become neutral atoms as the charge on the ions cancel each other out and are no longer ions, they are atoms.'
- 'I think that it forms by silver giving some or one of its outer electrons to the chlorine + so they both end up with full outer shells. Then they bond together with intermolecular forces.'
- 'They both share electrons as it is mutually beneficial to the both of them.'
- 'It changes to covalent bonding'.
- 'The two atoms react together and there [sic] charges go because they both have a charge of 1 so then the molecules become neutral.'
- 'They separate and break away from each other.'

Some students in the same group did produce more acceptable answers:

'I think that as silver (Ag^+) will be attracted to the chloride ions (Cl^-) making the compound have very strong intermolecular [sic] bonds as it is very difficult to separate a positive and a negative charge.'

'Heat is given off as forming bonds is an exothermic process and the ions are attracted towards each other by electrostatic forces'.

'I think that the silver ions + chloride ions form together into a strong crystal lattice.'

But such responses were in a minority, and some of the answers reflected the alternative conceptual framework for ionic bonding discussed in Chapter 8, *ie* that ionic bonding was considered to result from electron transfer:

'The outer electron in the silver transfers from the outer shell of the silver to the outer shell of the chlorine. This is called ionic bonding.'

Students in post-16 groups tend to have a better mental image of the particles present in the solutions (although some still suggest sodium chloride solution contains sodium chloride molecules and not ions, or hydrogen and hydroxyl – or oxide – ions instead of water molecules), and are less likely to give the more obscure types of explanations found among younger students. However, they are still likely to suggest that the formation of the ionic bond in the reaction mixture is due to electron transfer:

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'The silver ion donates an electron to the chlorine ion, and an ionic bond, complete transfer of electrons, is formed.'

'The electrons from the silver transfer to the chloride creating a electrostatic attraction between the 2 atoms.'

The idea that an ionic bond is necessarily the outcome of an electron transfer event (see Chapter 8) may be so ingrained that a student will explain the formation of the bond in silver chloride in this way despite demonstrating a clear appreciation of the species present in the reaction mixture. For example, one student in a class of 16–17 year olds correctly identified the species in the sodium chloride solution as Cl^- ions, Na^+ ions and water molecules, and in the silver nitrate solution as Ag^+ ions, NO_3^- ions and water molecules. This same student recognised that after the silver chloride was precipitated the solution would contain Na^+ ions, NO_3^- ions and water molecules. Yet the formation of the ionic bond was explained in terms of atoms (cf Chapter 6) and electron transfer:

'The silver and chlorine atoms, lose and gain an electron, respectively. To form charged ions (Ag^+ and Cl^-), positive and negative. This results in an electrostatic attraction between the Ag^+ ion and Cl^- ion to form an ionic bond.'

It not surprising, given this view of bond formation, that this student thought that each ion was only bonded to one counter-ion (see Chapter 8) in the precipitate:

'one chlorine ion to each silver ion. This is because the silver ion has a valency of one. Silver ion is +1 and it needs -1 to balance charge chloride ion is -1.'

As well as this probe, the materials on **Precipitation** also include a study task which takes students through this reaction step by step and includes a sequence of diagrams (*eg* see Figure 9.7) to help students visualise what is actually occurring at the level of molecules and ions in the precipitation process.

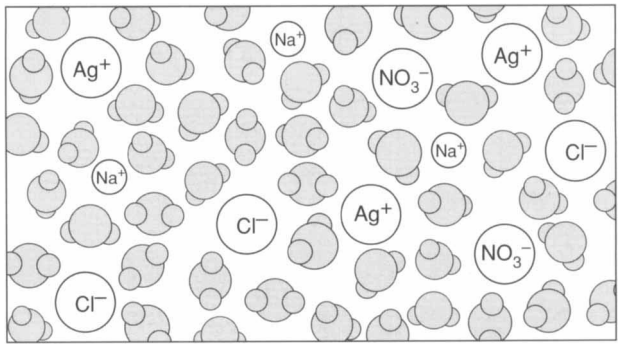

Figure 9.7 A diagram from the students' exercise on precipitation

How do reactions occur at the electronic level?

Often in post-16 level courses students are introduced to the idea of reaction mechanisms. Such mechanisms are very abstract (especially bearing in mind what has been reported above about some students having difficulty recognising the species present in reaction mixtures). Further, the common descriptions of reaction mechanisms introduce new formalisms regarding the representation of movements of single electrons and electron pairs (*ie*, so called 'curly arrows and fish-hooks').

In predicting reactions mechanism students need a quite sophisticated understanding of the patterns of electron density in molecules. Yet before they hope to apply such knowledge, they have to master the way such processes are formally represented.

One of the resources included in the companion volume is a diagnostic probe, **Reaction mechanisms**, comprising a pair of questions to test whether students are able to apply the formalism. Each question

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provides the student with the first step of a reaction mechanism, and asks the student to select the correct diagram from the options given (and to explain how they made the decision). The first question concerns an addition reaction, where the mechanism involves the movement of pairs of electrons. The first step is shown in Figure 9.8.

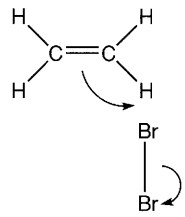

Figure 9.8 The movement of electron pairs

To predict the outcome of this stage, the student must appreciate where bonds are removed and formed, and the net 'gains' and 'losses' of electrons at each atomic centre (*ie* one carbon centre loses a 'share' in a bonding pair, one bromine centre gains fully an electron pair which it had only had a 'share' in).

The other question concerns a free radical mechanism, where electrons are considered to move independently and not in pairs (see Figure 9.9).

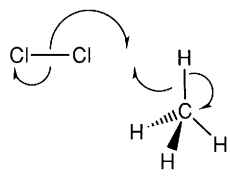

Figure 9.9 The formation of radicals

Again the student needs to appreciate where bonds are lost or formed. In this type of mechanism the atomic centres do not undergo net losses or gains of electrons (although, of course, there will be shifts in electron density patterns), but the students are expected to recognise any species which have unpaired electrons (at the carbon centre of the methyl radical formed, and one of the chlorine atomic centres).

When this probe was piloted for this publication some students were able to identify the correct diagram showing the next stage of the reaction, and to explain their choice.

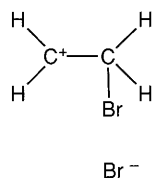

Figure 9.10 An intermediate stage in an ionic reaction mechanism

For example the correct diagram to follow the reaction step in Figure 9.8 is shown in Figure 9.10. Some students are able to select this answer, and explain their choice in terms of electron movements,

'because the double bond breaks and gives a pair of its electrons to one Br atom forming a bond. The other carbon from the double bond thus becomes positive. The electrons from the bond in the bromine molecule go to the 2nd Br atom therefore making it a -ve ion.'

However, selecting the correct response from among the eight offered did not necessarily imply a clear explanation,

'The electrons have moved towards the left [sic] carbon atom from the double bond which then moved through the first Br to the second. This results in the C atom on the right being δ+ and the free Br ions being δ–.'

Some students select the wrong answer, and their explanations may demonstrate a limited understanding of the mechanism and its representation.

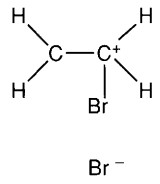

Figure 9.11 An alternative intermediate stage

So, for example, a student who selected the diagram reproduced as Figure 9.11, explained that

'because a plus charge is on the carbon as a result the differing electronegativity between bromine + carbon. The other bromine would gain a pair of electrons from the C-C double bond so would then be a separate ion.'

This response does not seem to call upon the electron movements shown in the question.

Some of the students who make the correct response seemed to be relying on recall rather than any understanding of the formalism. This approach is somewhat treacherous when the wrong responses look so similar to the correct ones (eg Figure 9.11 *cf* Figure 9.10, and Figure 9.13 *cf* Figure 9.12). So another student who incorrectly selected Figure 9.11 explained that,

'I remembered that the Br–Br bond separates & breaks the C=C bond to give the C a +ve charge. The bromine also becomes -ve charged when it is broken.'

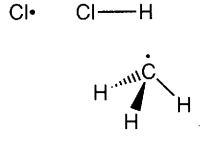

Figure 9.12 An intermediate stage in a free radical reaction mechanism

Figure 9.12 shows the intermediate stage that was the correct response for the second reaction mechanism (*ie* Figure 9.9). Again some students were able to select this option, and make fair attempts to explain their choice in terms of the electron movements,

'The Cl–Cl bond breaks, with one electron going to the left Cl, and one forming H-Cl bond. One electron leaves the H-C bond and completes the H-Cl bond, whilst the other electron moves to the C – leaving a Cl free radical, a HCl, and a CH_3 free radical'

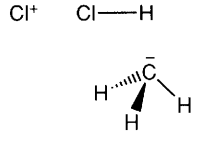

Figure 9.13 An alternative intermediate stage

RS•C

As with the ionic mechanism, some wrong responses demonstrated poor understanding of the formalism. For example, a student selecting the diagram reproduced here as Figure 9.13 was not paying heed to the meaning of the 'fish hook' arrows,

'The bond between Cl will break form[ing] Cl^- and Cl^+. one of the bond between C and H will break to form CH_3 and H^+. then H^+ and Cl^- will react to form HCl then leave Cl^+ and CH_3^-.'

Again, learning the mechanism by rote is not a fail-safe option. Another student wrongly selecting Figure 9.13 explained 'I have learnt this'.

Notes and references for Chapter 9

1. See the comments on chemical and physical change in Chapter 6.
2. As all reactions are technically reversible it has been suggested that the usual way of introducing reactions as unidirectional may be inappropriate (see note 3). If students adopt the implication that reactions 'go one way' then this could act as an impediment to later learning (see Chapter 4).
3. H-J. Schmidt, Should chemistry lessons be more intellectually challenging? *Chemistry Education: Research and Practice in Europe*, 2000, **1** (1), 17–26, available at **http://www.uoi.gr/conf_sem/cerapie/** (accessed October 2001).
4. R. Peters, An Introduction to Chemical Equations, available at **http://www.netcomuk.co.uk/~rpeters1/aufce.htm** (accessed October 2001).
5. A government funded project to research and disseminate good practice in teaching chemical equations, the GENIUS (Giving Equations New and Intentional Understandings) project, has been based at the University of Reading, directed by Dr. John Oversby.
6. It has been argued by Alan Goodwin, of Manchester Metropolitan University, that chemical symbols and formulae may still be successfully introduced, and accepted by students, as a scientific way of representing substances and reactions. In this approach the two types of equation may be used together, with each acting as a 'cue' for the other. Students would learn that $CuSO_4$ is another representation for copper sulfate, without initially being asked to consider why that particular formulae is used.
7. See, for example, the data from the English National Tests, published by the Qualification and Curriculum Authority on the TestBase CD-ROMs, eg QCA (2001) TestBase 2000.
8. H-J. Schmidt, In the maze of chemical nomenclature – how students name oxo salts, *International Journal of Science Education*, 2000, **22** (3), 253–264.
9. It is known that many 14–15 year olds have not developed an adequate scientific model of combustion as a chemical reaction of a substance with oxygen (note 10). Indeed, it has been suggested that 'seen from the perspective of the learner, the demands are so great that combustion must be regarded as one of the last things we should expect our pupils to understand' (note 11).
10. R. Watson, T. Prieto & J. S. Dillon, The effect of practical work on students' understanding of combustion, *Journal of Research in Science Teaching*, 1995, **32** (5), 487–502.
11. P. Johnson, Children's understanding of substances, part 2: explaining chemical change, *International Journal of Science Education*, (in press).
12. K. S. Taber, An alternative conceptual framework from chemistry education, *International Journal of Science Education*, 1998, **20** (5), 597–608.
13. The figures given relate to reaction at 298K and are from J. G. Stark and H. G. Wallace, *Chemistry Data Book, 2nd Edition in SI*, London: John Murray, 1983.