Chemical axioms

In this chapter some of the fundamental principles used in chemistry are considered. Research into learners' ideas about these key ideas are discussed, including the types of responses that were found when some of the classroom resources included in the companion volume were used in schools and colleges.

The chemist's creed

This chapter is called Chemical axioms because the principles discussed here may be considered to be the basic 'tenets' of chemistry: the key ideas upon which the whole subject is built. Learners who do not share these 'beliefs' - because they hold alternative conceptions -will find it very difficult to understand chemistry in the way teachers would want.

Material, energy and substance

One of the most basic discriminations in science is between energy and matter - although this is not a distinction that is always clear to students.[1] Although (since Einstein) it has been realised that the division is not absolute, it is still very important at the level of secondary and college science. Energy is known to be a difficult topic for learners, and younger students may not fully appreciate that heat (for example) is not a material substance.[2] Research also shows that children do not readily recognise that air and other gases are material - especially when there is no perceptible movement (such as a draught).[3] Something that cannot be seen, heard, felt, smelled or tasted (such as still air) may not seem to exist.

By the time students enter secondary school they should have overcome such problems, and recognise gases as material, and energy as something distinct from matter. Yet it is worth teachers of lower secondary groups being aware that a degree of confusion may still be present for some students.

A more common problem at this level is the way that chemists tend to use the term substance (or pure substance). This is a technical term in science. However, like many other words used in science, students will have heard the word 'substance' used with a more general everyday meaning akin to 'essence' or 'flavour'. To a chemist a substance has a definite chemical composition. To the learner any material may be considered a substance.[4]

To the chemistry teacher it is clear why sulfur, water and carbon dioxide are pure substances, but not wood, nor milk, nor air. Yet this distinction is based upon an appreciation of the composition of these materials at a sub-microscopic level that is not immediately available to the student. It is hard for the chemistry teacher not to think about any material in terms of its composition, but students are more likely to focus upon a material's appearance and its common uses.

Elements, compounds and mixtures

It is important to get learners thinking along 'chemical' lines, and lower secondary students are usually expected to develop an appreciation of the meaning of the terms 'element', 'compound' and 'mixture'. Yet - as will be discussed below - this distinction relies upon an appreciation of composition at two distinct and imperceptible levels.
Included in the companion volume is a set of classroom materials on **Elements, compounds and mixtures.** This includes diagnostic probes for (a) eliciting learners' understandings of these key terms and (b) applying their definitions to diagrams showing particles in examples of elements, compounds and mixtures. The examples are limited to molecular materials *(ie* not including giant structures) in order to avoid too much

complication at this stage. The materials also include a teaching exercise. The activity requires students to interpret diagrams representing molecules.

A wide range of types of representation are used to show molecules in texts commonly used by students (see Chapter 7). Although this is potentially confusing for students it can also provide a context for teaching about the nature of scientific models (a topic considered in more detail later in this chapter). The various types of diagram used to show molecules each emphasise certain aspects of the molecules, and ignore others. Students need to appreciate that molecules do not 'look' exactly like any of these pictures, and that we select a suitable image to help explain or explore a particular aspect of the molecules.

For these particular classroom materials it was felt that modelling molecules as atomic cores in a cloud of electrons was suitable (see Figure 6.1). This type of representation would enable students to clearly identify discrete molecules in the figures, and to see how many types of atomic core were present in a molecule.
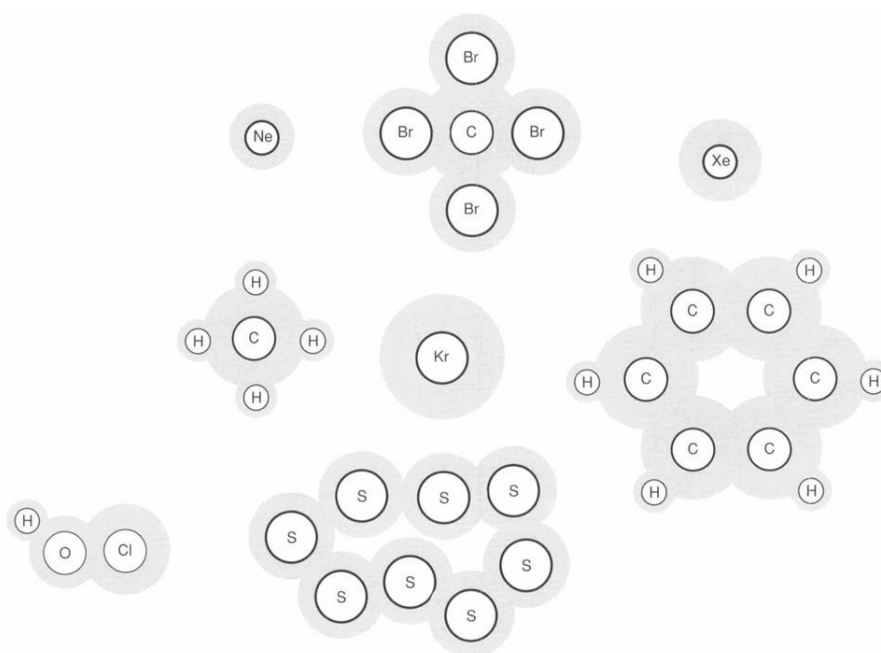

Figure 6.1 Representations of some molecules

When the materials were piloted in schools it was reported by teachers that students often had difficulty explaining the key terms adequately. (This is not be surprising in view of the difficulties teachers have in agreeing what terms like 'molecule' mean - see Chapter 2.) One teacher who was 'surprised at [the] confusion of key terms' suggested that teachers should pay more attention to the terminology used in the classroom. Another teacher who reported 'considerable uncertainty about definitions and the distinction between atom and molecule' went on to comment that this was still a problem with post-16 students.

A flavour of this confusion may be seen in the following definitions of a mixture from students in a class or 13-14 year olds;

'[A mixture is] something which is made up from two or more different kinds of atoms and molecules and compounds.'

'[A mixture is] a substance with two or more different kinds of atoms [sic] which are not chemically joined together.'

'[A mixture is] a substance that contains two or more different atoms joined together.'

'[A mixture is] a mix of lots of different molecules in an atom.'

In some cases, students seem to be struggling to work out the scientific basis of the distinctions because they do not appreciate (a) that the distinction between 'atom' and 'molecule' does not parallel the distinction between 'element' and 'compound', and (b) they are not aware that they have to make discrimination at two levels (ie the number of types of molecules present in a sample, and the number of types of atomic core present in a single molecule).

In this same class of students;

- tetrabromomethane (CBr,) was classified as a mixture because 'there are two types of element' or 'different types of atoms in it';
- sulfur (S,) was considered a compound due to the number of atoms in the molecule;
- a mixture of two hydrocarbons (CH, and C,H,) was classed a compound as there were 'two different types of atoms chemically joined together';
- a mixture of two inert gases (Kr and Ne) was judged an element as 'the molecules are singular';
- and the same mixture of two inert gases (Kr and Ne) was also judged a compound as there were 'two types of atom'; and
- molecules of a compound of three different elements (HOCl) was classed as a mixture as there were 'more than 2 types of atom' or 'more than two types of element joined together'.

At least one student in this group seemed to have simplified the task of distinguishing the three classes in terms of the number of types of atom present:

Number of types of atom	Type of material
1	Element
2	Compound
3	Mixture

This student recognised the figure of S, molecules as an element ('only one type of atom') but considered both the mixture of noble gases and the mixture of hydrocarbons as compounds ('there is two types of atoms') and the diagram showing HOCl molecules as a mixture (due to the 'three types of atoms').

This student recognised the figure of S, molecules as an element ('only one type of atom' but considered both the mixture of noble gases and the mixture of hydrocarbons as compounds. ('there is two types of atoms') and the diagram showing HOCl molecules as a mixture (due to the 'three types of atoms').

The probes and study task on **Elements, compounds and mixtures** deliberately include some examples of molecules that students would not normally have been familiar with, to ensure that they are applying their criteria for classifying materials, rather than just using recall. This includes using some examples of somewhat more complicated molecules, such as the benzene molecule (Figure 6.2).
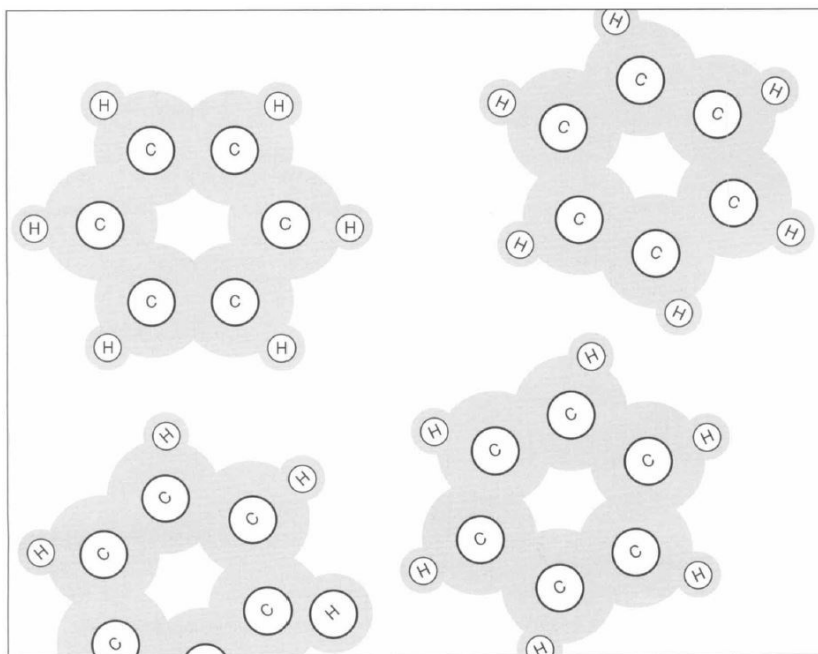

Figure 6.2 A representation of molecules of a pure substance (benzene)

One teacher reported that some of her (15-16 year old) students 'found the complex molecules (benzene) difficult to accept as a single substance'. In view of some of the responses reported above, it might be suggested that it is important that students do meet a wide range of examples of elements, compound and mixtures, and not just the simpler examples such as diatomic molecules and binary compounds. When students only meet a restricted range of examples, then they may well form alternative meanings for basic chemical terms as there will be insufficient counter-examples for them to have reason to question their own working definitions (see Chapter 2). As always, skilful teaching requires finding the optimum level of simplification for students to understand the key ideas without over-simplifying the science to be taught.'

The teaching exercise for Elements, compounds and mixtures is quite lengthy (with a good deal of reading) but includes spaces for students to demonstrate their understanding as they proceed. It was designed with the following principles in mind:

A. that it was important to break the task down into two discrete aspects - distinguishing a mixture from a pure substance, and then further dividing the single substances into those that were elements and those that were compounds;
B. that defining elements and compounds in terms of whether they could be 'broken down further by chemical means' was not very helpful, and a particle based model should be used.

The first point was very important in view of the comments made above about how learners may only have a vague idea about what is meant by the term 'substance'. These distinctions

can only make sense to learners if they are asked to consider a particle model, and, even then, two levels of scrutiny are needed (see Table 6.1).

Looking at:	If the same:	If different:
The types of molecules	a single substance	a mixture
The types of cores in a single molecule	a molecule of an element	a molecule of a compound

Table 6.1 The summary table presented to students

Firstly the learner must consider the types of particles present (at the level of molecules) and decide whether one or more type of molecule is present. If the several types of molecule are present, then the material represented is a mixture regardless of whether the molecules present represent elements, compounds or both.[6]

Where only one type of molecule is present it is then necessary to look at those particles (the molecules) in more detail. Molecules comprise of one or more atomic cores enveloped by a cloud of electrons (see Figure 6.2). Students simply consider whether a molecule has a single type of atomic core or several types - and is therefore a molecule of an element or of a compound.

Defining elements and compounds

One of the classroom activities included in the companion volume, Definitions in chemistry, is designed to explore students' understanding of common definitions of basic chemical terms (ie element, compound, atom and molecule). This exercise is intended for students who have progressed beyond the stage where they will benefit from the classroom exercises on Elements, compounds and mixtures discussed above.

Some of the definitions included in this activity were derived from school textbooks or common reference books. Some of these definitions are dubious, ambiguous or just unhelpful (see Chapter 2). Also included in the exercise were some examples of definitions that were derived from students' comments, and these are lacking in accuracy or precision. For example, the following definition of a compound was included: 'Is made of 2 elements mixed together'.[7] One student in a group of 14-15 year olds judged this as correct, though not helpful. This judgement was explained,

'I don't think it is very helpful for somebody learning science because it can be made up of more than one substance'.

A classmate judged this statement as correct and helpful,

'It is correct because compounds are 2 or more elements mixed [sic] together. An element is single, they make up compounds.'

Another classmate thought the definition was wrong and unhelpful, because,

'It could be more than two elements mixed [sic] together.'

These three responses highlight just how difficult these ideas are, and the language demands they place on students. The first comment seems to suggest the student misread

the definition (although, as always with written responses, direct questioning would be needed to confirm this interpretation).

The second ignores the limit on two elements in the definition and agrees that a compound is a mixture. The final student has spotted that the wording of the definition does not allow ternary (or higher) compounds but has also agreed with the notion of a compound being a mixture.

Models in teaching science

It is important that learners become familiar with using the molecular model of matter if they are going to be able to make sense of much of the secondary science curriculum. Research shows that students often have only a very limited idea of the way scientists use models. [8,9,19,11,12] At the start of secondary education many students will consider models to be little more than imperfect copies of an object, often made larger or smaller than the real thing. Scientists and science teachers actually use models in a number of ways that go well beyond this. For one thing scientific models focus on selected aspects of the system being modelled and deliberately ignore others that are considered irrelevant. As what is relevant changes with context, a particular model is designed for a particular purpose - for example to explain certain limited aspects of a phenomena. This means that it is quite acceptable to have multiple models which are mutually inconsistent, but which are used to explain different features of the same system.

Another aspect of scientific modelling is that models are mental tools, and so scientists do not always design models to be 'correct', but sometimes rather to test ideas. A model which 'does not work' when it is set up and explored - because it does not match the phenomenon being investigated – is like an incorrect hypothesis. Such a model can still be useful, as we can learn a lot from it by elimination. Students may not appreciate that these models are designed as exploration tools, and that scientists 'play' with the models in order to learn about the phenomena. In contrast, a student is more likely to assume that a model is intended to be as accurate a representation of 'reality' as possible, and to expect those models met in school science to have already been 'proved' correct.

Clearly it is useful for teachers to emphasise that models are hypotheses about the world which may be limited, partial, and even sometimes 'wrong'. This will help students to understand the limitations of models, to accept multiple models, and to appreciate a little more about the nature of science itself.

One of the most important models (or perhaps, collections of models) used in chemistry is the molecular model: the idea that matter is not continuous but made up from discrete particles that are much too small to be seen.

The particle model of matter

Although the molecular model is a central idea in science, and is very familiar to chemistry teachers, we must not be complacent about how problematic particle ideas are for students.[13] Research shows that students do not tend to spontaneously use relevant particle ideas in explaining chemical phenomena[14]. This is understandable when the difficulties that students face learning the model are considered.

The word 'particle' is not very helpful, as it is used for small (yet still visible and macroscopic) particles such as salt grains or dust specks, as well as a collective term for molecules, ions etc.

Research shows that this leads to confusion for many students.

A more intractable problem is deciding what the particles are, from which all materials are made are. Teachers like to have a single term that they can use when introducing the molecular model to students, but this can lead to rather imprecise use of language - as in the following classroom observation,

'the teacher conjured up an image of diffusion in solutions by referring to blue copper sulphate 'atoms', and colourless water 'atoms' wriggling slowly past each other at the junction of the two layers[15]

For many substances it is quite correct to refer to the particles as molecules. This would be appropriate for sugar, water, sulfur, oxygen etc. However, not all materials are molecular. In diamond it is quite possible for the 'molecule' to be a visible entity. In metals such as iron, and salts, such as sodium chloride, there are no molecules.

This is not a pedantic point, as learners who are taught that 'everything is made of molecules' will expect iron and sodium chloride to contain molecules, which can be a problem at a later stage in science learning (see Chapters 7 and 8).

One alternative is to use the word 'atom'. It is common for chemistry books to suggest that everything is made of atoms (see Figure 6.3), but this is also problematic. Very few substances (ie the noble gases) are actually composed of atoms per se. In molecular materials the discrete particles present are molecules, and it is not helpful if students assume that something like oxygen comprises of oxygen atoms (see Chapter 10).
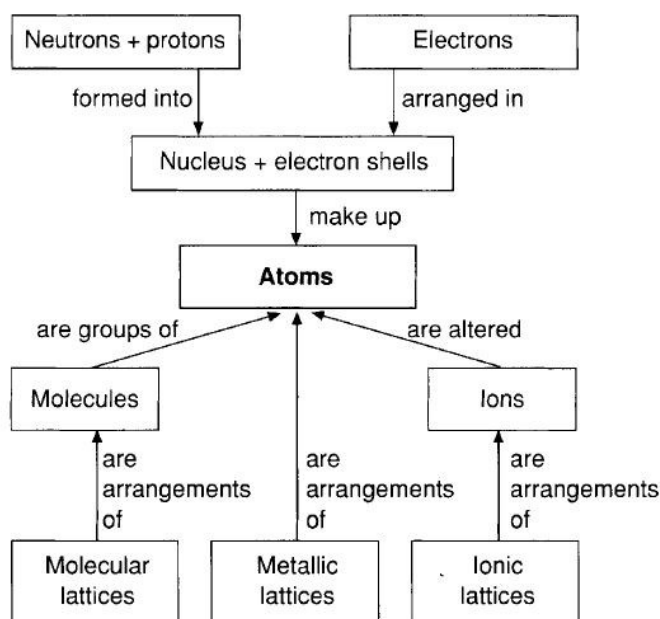
Figure 6.3 Seeing atoms as the building blocks of matter

Although we might commonly say 'a molecule of water contains two atoms of hydrogen and one of oxygen', it can be argued that this is not quite correct either. In a water molecule some of the electrons (the bonding electrons) are not associated with a single nucleus and should not be considered part of a particular atom. This may again seem pedantic, but students have been found to take the 'molecule contains atoms' idea literally, and to assume

that each electron 'belongs' to and is 'part of' only one of the atoms. This leads to false ideas about the interactions in the molecule (with electrons only being attracted to their own nuclei!) and about bond fission always being homolytic (because a bond always breaks so the electrons go back to 'their own' atoms!)[16]. Similar ideas also lead to common misconceptions about ionic bonding (see Chapter 8) and to problems understanding precipitation reactions (see Chapter 9).

The atom is also an inappropriate label for the particles in salts such as sodium chloride or metals such as iron, both of which are better understood to contain ions -with, in the case of metals, delocalised or lattice electrons which are often referred to as a 'sea' of electrons (see Chapter 8). Even in the case of diamond there are no discrete atoms present, although again we find students may sometimes assume that diamond does comprise of separate carbon atoms (see Chapter 7).

It would of course be correct to say that all matter consisted of protons, neutrons and electrons, and we would want students to learn this during their secondary careers, but this is not considered an appropriate treatment at an introductory level.

All the structures that students are likely to meet in chemistry can be described in terms of arrangements of atomic cores and outer shell electrons (see Figure 6.4), but this is a way of conceptualising matter that will take time to be acquired once the simpler, if inadequate, 'everything is made of atoms' notion is accepted.
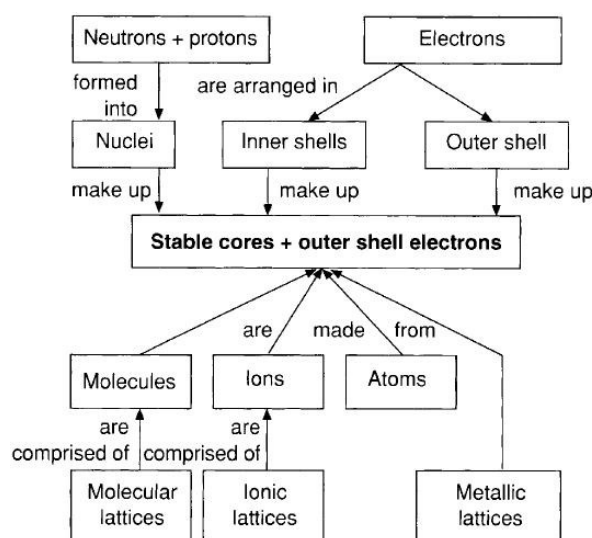
Figure 6.4 A more scientific, but more complex, model of the building blocks of matter

It is difficult to provide definitive advice in this topic as there does not seem to be an obvious solution to the problem. All of the alternative approaches are fallible and are likely to lead to students acquiring inappropriate ideas unless presented very skilfully.

Probably the best approach is to refer to 'molecules' in introductory work, and use suitable examples, but to make it clear that the particles in some materials are slightly different. It is not necessary to give any details (although the example of metals might be mentioned), but it is sensible to emphasise to students that they are being taught an important, but incomplete model, which will be developed later in their education. At a later stage of the students' education, when the ideas of chemical structure and bonding are being introduced,

it may actually be more sensible to first consider the simplest case of metals, and to teach about solid structures which are arrays of simple molecules last (see Chapter 10).

Defining atoms

One of the classroom activities included in the companion volume, Definitions in chemistry, is designed to explore students' understanding of common definitions of basic chemical terms (ie element, compound, atom and molecule) - something that is inherently problematic (see Chapter 2). As discussed earlier in this chapter, this resource asks students to comment on definitions taken from books and from students' comments.

For example, the following definition was given by a student setting out on a post-16 chemistry course,[17]

'an atom is the simplest structure in chemistry. It contains a nucleus with protons and neutrons, and electrons moving around shells.'

This was included as an item in the Definitions in chemistry exercise. One student in a class of 14-15 year olds was not sure if this was a helpful definition as 'the electrons move around in shells, not around shells'. A classmate judged it as a correct and helpful definition: 'It's to the point, clear and fairly easy to understand'. Neither of these students questioned the idea that the atom was the simplest structure in chemistry. Indeed, another classmate agreed with this point, whilst pointing out that the nucleus also had structure,

'atoms are simple structures, the nucleus is made up of protons and neutrons and electrons orbit it in shells.'

This same type of internal contradiction was present in another of the definitions included in the exercise. This was also based on the definition provided by a student commencing a post-16 chemistry course. For this student, the atom was the:

'smallest particle that can be found. Made up of protons, neutrons and electrons'

Yet, this contradiction is not obvious to some students. When this item was considered by students working through the Definitions in chemistry activity, one of the 14-1 5 year olds judged this as a correct and helpful definition, and explained:

'They are the smallest possible thing and they are made up of protons neutrons and electrons.'

As discussed above, there is a tendency for the term atom to be used in introductory science as a catch-all term for atoms, molecule and ions, and students readily accept the 'everything is made of atoms' mantra, even though this is (at best) a gross over-simplification. These examples show that some students are also happy to accept notions of atoms being the simplest structure possible and the smallest particles that can exist - even when they 'know' they contain simpler structures and smaller particles. That such contradictions do not seem to worry these students is another indication of how little sense many students make of our molecular models of the world.

Student confusion over molecules and ions

Students often find it difficult to think in terms of the images of molecules and the like that seem to come so readily to experienced teachers. For example, one of the diagnostic probes in the companion volume - part of the materials on Precipitation - asks students about the species present in sodium chloride solution. It became clear during the piloting of this resource that some 14-16 year old students found it very difficult to work out which molecules and ions were present in solutions. The students were presented with a diagram of solid sodium chloride (see Figure 6.5) which was accompanied by text informing them that 'the particles in sodium chloride are sodium ions (Na^+) and chloride ions (Cl^-)'.
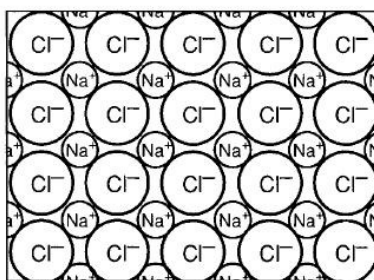

Figure 6.5 Particles in solid sodium chloride

The students were also provided which was accompanied by text with a diagram representing molecules in water (see Figure 6.6), informing them that 'the particles are water molecules'
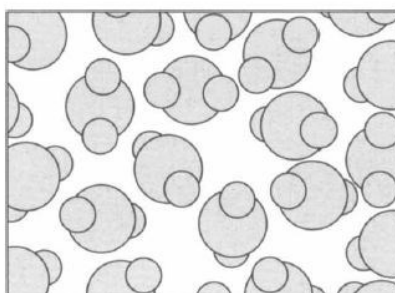

Figure 6.6 Particles in liquid water

It is worth noting here that there are genuine problems in trying to represent liquids in simple particle diagrams. This representation could be criticised as exaggerating the space between molecules. However, as liquid molecules do not form 'layers' a more accurate diagram would either have to show complete molecules from different 'depths' in the liquid (which would overlap and complicate the diagram), or would need to be a true two dimensional cross section of a slice through the liquid - so that different molecules would be sectioned at different points and would all seem to have different shapes. As discussed above, all representations are models of selected aspects of what is represented - and opportunities should be taken to raise the limitations with students.

In the Precipitation probe, the first task set to students is to list the species present in sodium chloride solution. The students are asked:

'Sodium chloride dissolves in water to give sodium chloride solution. What particles (such as particular atoms, molecules, ions) do you think are present in sodium chloride solution?'

Although the probe was primarily concerned with students' ideas about what happens when an ionic precipitate formed, it is clearly necessary for them to appreciate which species are present in the two solutions which are mixed in the reaction. The first questions were

designed to check students were aware which species were present, and to focus their thinking on this as a relevant aspect of the process (see the comments on scaffolding PLANKS in Chapter 5).

Clearly the main species present in sodium chloride solution are sodium and chloride ions and water molecules. In view of the degree of cueing (or scaffolding) provided by the diagrams and accompanying text, it is not surprising that many students were able to give the correct response. However, by no means all students were capable of working this out. Among the responses suggested in one class of 14-15 year olds in one school were the following:

- sodium ions; chloride ions; hydrogen ions; hydroxyl ions
- Na^+ ions; Cl^- ions; water molecules; sodium chloride ions
- sodium ions; chloride ions; hydrogen ions; oxygen ions
- sodium atoms; chlorine atoms
- molecules of NaCl and H_2O molecules
- sodium ions; chloride ions; hydrogen molecules; oxygen atoms
- sodium ions; chloride ions; hydroxyl ions.

Although some keen students could possibly be aware that some ionic association may occur, and that water has a degree of dissociation, this can not explain responses including NaCl molecules instead of ions, or hydrogen and hydroxyl ions but not water molecules. These students were generally struggling to report what would be present when solid sodium chloride (which they were told consisted of sodium ions and chloride ions) dissolved in water (which they were informed comprises of water molecules). Other students in this class seemed to be struggling to give an answer in particle terms at all, suggesting that the solution contained hydrogen [sic]oxygen; sodium; chlorine or 'a solid'.

Defining molecules

One of the classroom activities included in the companion volume, Definitions in chemistry, is designed to explore students' understanding of common definitions of basic chemical terms (ie element, compound, atom and molecule) - something that is inherently problematic (see Chapter 2).

As discussed earlier in this chapter this resource asked students to comment on definitions taken from books and from students' comments.
One of the definitions of 'molecule' included in the activity was derived from the comments of a student, who had defined a molecule as 'formed by two atoms bonding together'. That this only allows diatomic molecules might seem an obvious limitation. Again, however, students may not recognise this problem. One student judging this as correct and helpful explained that it is 'quite easy to understand [and] doesn't complicate matters later on'. Even this uncomplicated definition elicited some evidence of students confusing the molecular model with the macroscopic phenomena. One classmate thought that this definition was 'correct, but not very clear. [As] It doesn't explain the different between compounds and molecules'. A compound would be said to be formed from elements, not atoms, of course. Another student in the group thought that the definition was both correct and helpful because it was 'like water which is made of 2 elements' - although a molecule of water, of course, has three atomic centres.

Once again, there is evidence of students confusing the most basic ideas in chemistry, and not being able to clearly distinguish between the level of substances and their representation through molecular models.

Applying the molecular model

Research shows that even when learners may seem to have acquired the 'everything is made up of particles' principle, there can be serious flaws in their understanding of what this is meant to imply. For example learners may suggest that the substance is found between the particles - so in water there are water particles with water in-between them! Alternatively they may just assume there is air between the particles (after all, it is said that 'nature abhors a vacuum'!)[18] A related problem occurs when students think about the bonds between the particles in a material -which they often imagine as material links such as springs or elastic (see Chapter *8),* showing that they have not really taken on board the full implications of the molecular model.[19] These types of ideas show just how abstract and far-removed from everyday experience the molecular model is.

Even when students have 'got' the particle idea, and realise that the particles are all that is there (not particles embedded in the substance, or separated by air), they may fail to appreciate the value of the model to science. The particle model is so successful because a large number of macroscopic properties of substances can be explained in terms of the conjectured properties of the systems of particles (see Figure 6.7).[20]
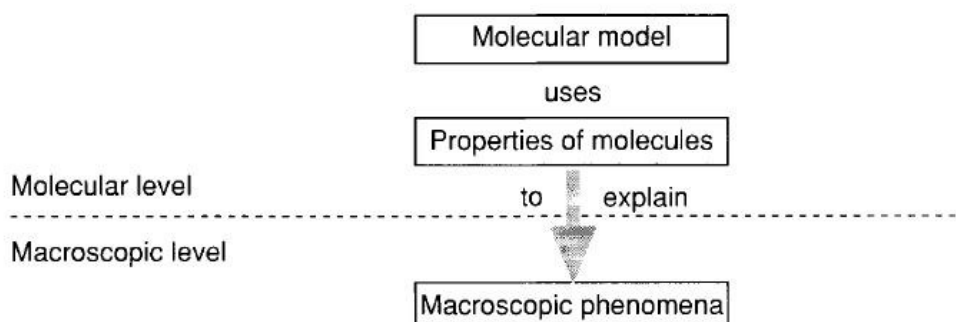
Figure 6.7 How science uses the molecular model

Without appreciating this point, the rationale of the molecular model is lost. And yet there is a great deal of research that shows that students commonly do fail to understand this. Although learners will learn to talk about particles when explaining macroscopic phenomena, they often simply transfer the property to be explained to the molecular level (as in Figure 6.8).
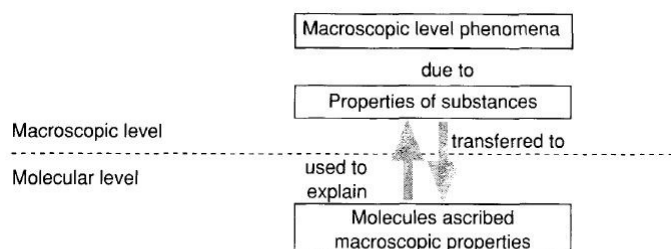
Figure 6.8 How many students apply ideas about molecules

There are many examples of this that have been reported. So materials are said to expand on heating because their particles expand, for example. In science we teach students that thermal expansion can be explained on a particle model (Figure 6.9).
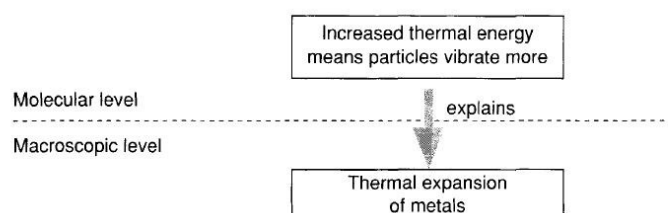

Figure 6.9 An example of how students are expected to apply molecular ideas

Students generally come to accept this model, even though it has an obvious logical flaw (if the particles are vibrating synchronously the increased vibrations need not change the overall volume!) It is only later (for those who study post-1 6 level physics) that a more comprehensive version of the model is provided (Figure 6.10):
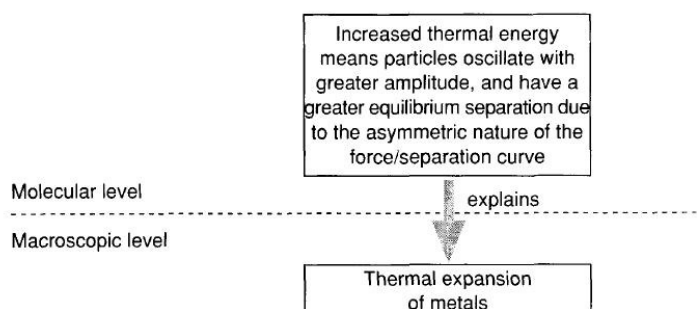

Figure 6.10 A post-16 level explanation of thermal expansion

Although students seldom query the simplified explanation given in Figure 6.9, this is more likely to be a result of their failure to visualise the model, rather than finding the argument convincing. The type of particle-based explanation that many students themselves suggest follows the pattern described above (see Figure 6.8), of transferring the property to be explained, in this case expansion on heating, to the particles in the model (see Figure 6.1 1).
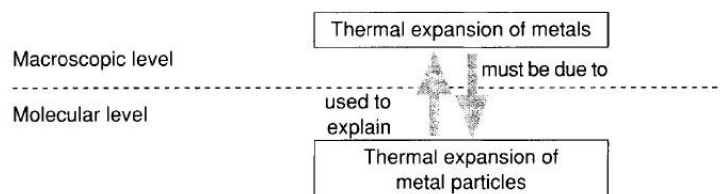

Figure 6.11 A common way for students to explain thermal expansion

This type of approach shows how students commonly miss the point of having a molecular model. The idea that 'materials expand on heating because the particles expand' is regarded as a common misconception. This is a little unfortunate for students as if the metal (or other material) is made up of particles with 'nothing' between them, and if the bulk material gets bigger on heating, then on average each particle must clearly take up more space. This would seem to suggest that they get bigger! This could be considered to be at least as sensible a suggestion as the accepted response (Figure 6.9) at this level.

Even though I have sympathy with students in this particular case, there are many other examples where this approach is clearly unhelpful. Individual molecules may perhaps be considered to have a smell, and some are coloured (although colour is often a property of higher levels of organisation), but there are many properties of materials that are due to the arrangement of, and type of bonding between, particles rather than just the particles themselves.

Among the resources included in the companion volume is a classroom probe, Iron - a metal, which asks students to judge the truth of a number of statements about the properties and structure of iron. Some of the items test whether students will find acceptable explanations of metallic properties which transfer the macroscopic property to constituent particles (ie as in Figure 6.8). When this activity was tackled by one group of 14-15 year olds, it was found that a majority of the students agreed with a number of explanations of bulk iron properties in terms of the individual atoms rusting, conducting electricity and reflecting light:

- The reason iron rusts is that iron atoms will rust if exposed to damp air.
- Iron conducts electricity because iron atoms are electrical conductors.
- An iron atom will reflect light, and so freshly polished iron shines.

Chemical and physical change

Another basic distinction which 11-14 year old students are expected to develop is that between chemical and physical changes. Again we find a fundamental distinction which is problematic for teachers and learners. In Chapter 2 we saw how this basic distinction becomes difficult for teachers when they are asked to classify changes such as dissolving or driving water of crystallisation from hydrated salts.

Although the difference between these two types of change is often considered significant, it is not easy to provide learners with simple rules for making the distinction. Two common types of definitions are used (Table 6.2).

Physical change	Chemical change
easily reversed no new substance	not easily reversed new substance formed

Table 6.2 Key criteria for distinguishing chemical and physical changes

Clearly chemical changes can be reversed, although sometimes only under extreme conditions. However, those chemical reactions with a very low Gibbs free energy change may be quite readily reversed. Conversely, mixing is considered a physical change, but separating some mixtures (such as in crude oil) may not appear to be 'easy' to students. From the teacher's perspective, of knowing which changes are considered ('meant to be') physical and which are considered ('meant to be') chemical, then the judgement of whether reversal is easily achieved may well sometimes be prejudiced!

Similarly, deciding whether a different substance is formed during a change will be easier for the teacher, calling upon privileged information that may not be available to the students.[21] It is a fundamental tenet of chemistry that - for example - steam, liquid water and ice are the same chemical substance despite having different physical properties. (In principle they have the same chemical properties, but this is not easily shown: does ice react with sodium

without melting? When magnesium is reacted with water there is no obvious reaction until the water has boiled.)

A change of state is a physical change as the same substance is present before and after the change. And yet, at the start of their chemical education, students only have it on trust that ice and steam are both forms of water, yet (for example) rust is not the same substance as iron. Again these distinctions only become 'obvious' when viewed from the 'molecular' level. Steam, liquid water and ice all contain the same basic particles - water molecules. This means that it can be argued that it is often actually easier for students to judge whether a change is physical or chemical on the basis of particle model diagrams than by looking at the process itself!

Two other criteria that could be introduced here (Table 6.3) are equally problematic.

Physical change	Chemical change
easily reversed	not easily reversed
no new substance	new substance formed
no bonds formed / broken	bonds broken and / or formed
modest energy change	large energy change

Table 6.3 Criteria for distinguishing chemical and physical changes

The idea that in a chemical change bonds are broken and/or formed seems sound. Yet it is not so clear that a physical change does not also involve bond breaking. At lower secondary level we probably only think of covalent, ionic or perhaps metallic bonds as being chemical bonds. Yet, later, we may wish students to learn about hydrogen bonding, van der Waals forces, and solvent-solute interactions. Research shows that learners may find it difficult to expand their definition of chemical bonds to include these categories (see Chapter 8), and so it probably unwise to restrict our meaning of 'bond'.

Clearly physical changes such as changes of state, do involve the breaking and forming of bonds - this is why ice, water and steam are so different despite being made up of the same water molecules.

The energy change criteria is just as problematic: although some chemical reactions (eg the hydrogen/oxygen explosion) may obviously involve large energy changes, and some physical changes (eg evaporation of a volatile liquid) may seem to involve little energy transfer, it is possible to suggest counter examples. The rusting of iron seems no more an energetic process than evaporation, and students are warned about the dangers of scalding themselves on steam, because of the large amount of energy released when it condenses.

Some teachers feel that the chemical /physical change distinction is an unhelpful one which should not be taught. However, at the moment it is a required part of the science curriculum for many students, and so must be covered in class. The best that can be said is that these concepts have 'fuzzy' boundaries (see Chapter 2).

Chemical and physical changes are not categories that obviously exist in nature. It is chemists who find it useful to impose these artificial categories upon the wide range of changes that can occur to, and between, substances!

One of the class resources provided in this publication, Changes in chemistry, is a probe to test whether students can recognise which changes are considered to be chemical and which are said to be physical. In view of the problems discussed above, this probe provides 'before' and 'after' diagrams based on particle models to help students make their decisions.

Although it is possible to avoid some of the difficulties in this way, and by limiting examples to clearcut cases, it seems sensible to emphasise to students that:

- the distinction between physical and chemical change is just one that chemists sometimes find useful;
- although they will only be expected to judge examples with clear answers, some changes they will meet do not fit easily into one category.

When the probe was piloted in schools it was found that students were often able to demonstrate acceptable ideas. So freezing liquid nitrogen was a physical change because;

'no chemical bonds have been broken ...'

'the particles are the same they have just been restructured'

'the chemical formula has not been changed...', and

'...it is the same substance...'.

Burning magnesium was considered to be a chemical change, 'because the Mg and 0 has bonded they have a chemical bond and can not be changed back.

Magnesium oxide has been produced a new substance.'

However, some of the problems with the chemical/physical distinction were reflected in students' responses. This may be seen in the responses from some students in groups of 13-14 year olds. For example, although most students recognised that combustion of magnesium was a chemical change, there were some dissenters. Some students were able to see this as a reversible process. One focused on the perceived increased activity of the particles, 'the molecules have been heated and so they are very active but if you cool them down they will be able to settle.'

Other students thought that 'magnesium oxide can be changed back to magnesium and oxygen'

and one suggested that

'you could do a displacement reaction to get the oxygen away from the magnesium oxide. You would be left with oxygen and magnesium.'

The case of sodium chloride dissolving produced a range of responses from students seeing this as a chemical process. It may be relevant here that students often use the same

terminology for the process of a solute dissolving in a solvent, and, for example, a metal reacting with ('dissolving in') an acid.[22] A number of students argued along the lines that 'you are unable to turn the substance back to it's original form as it is mixed in with the water.' Whereas a simple distinction based upon reversibility implies a clear demarcation, what we find when students try to apply the reversibility criterion is that some see chemical changes as reversible (suggesting chemical methods that are 'not allowed'), and others consider physical changes as irreversible (presumably not considering a technique such as distillation as 'allowed'). This should not be surprising when we realise that the reversibility criterion is inherently tautological, ie,

- a chemical change cannot be reversed except through a chemical change;
- a physical change can be reversed through a physical change.

When it is spelt out in this way it is clear that such a criterion needs to be learnt through familiarisation with conventional examples, and cannot be based on definition (*cf* the comments on defining concepts in Chapter 2).
Some students gave other arguments for considering dissolving of an ionic substance as a chemical change. Some noted that bonds had been broken in the sodium chloride,

'The Cl & Na are no longer bonded together and are able to move around separately from one another.'

'the Na and Cl have been split up and the atoms are more widely spaced and in a mixture the bond between the Na + Cl has been broken'

and one student suggested that new bonds had been formed (which is technically correct, as solvation had occurred), 'the different atoms have bonded together & formed a new pattern.'

The Changes probe was also undertaken by a group of High School students in Greece. Although there could be some doubts over the additional demands of undertaking the probe in a foreign language (ie English), it is interesting that most of the group considered the dissolving of sodium chloride to be a chemical change (11/14, with the other 3/14 considering this change to be physical). As with the British respondents, there were some attempts to justify the classification in terms of pertinent criteria,

'some sodium chloride is added to a beaker of water and left to dissolve and so the molecule are connected'

'water (H_2O) divides NaCl into its components Na, Cl so it's substance change'

Although student responses did reveal some genuinely alternative ideas about the processes discussed (such as weight changing during a physical change, or a chemical change being one where 'you cannot actually see the change'), this particular probe might be considered as most useful for diagnosing students' inappropriate application of the fuzzy set of criteria used in the science curriculum for distinguishing chemical and physical change.

Conservation in chemistry

Some of the most basic principles in science are conservation laws. In physics classes students learn about conservation of energy, and this principle apples in chemistry as much as elsewhere. At post-16 level, students will be taught that mass can be considered as a form of energy, but at secondary levels energy and mass are considered as separate.

The conservation of mass is a very central and basic idea in chemistry. Its application is (again) tied closely to particle ideas. The fundamental particles from which substances are composed have fixed mass, and the mass of a sample of material is the sum of the masses of all the constituent particle masses.

Two key teaching points, then, are that during a chemical reaction (or during a physical change):

- the same fundamental particles are present at the end as at the start; and
- the total mass has not changed.

The particles are rearranged, but the new configuration is made up of the same fundamental particles, and therefore has the same total mass, as before.

Of course, the 'particles' here are not molecules, but the atomic constituents. As the mass of the electrons is less than 0.1%, and as there are no nuclear transformations being considered, the mass in chemical reactions may be considered to 'follow' the atomic cores, or nuclei. (So we can use relative atomic masses to calculate reacting masses, and to find percentage yields etc.)

One of the classroom exercises included in the companion volume, Mass and dissolving, presents an example of a type of change where students should realise that mass must be conserved: dissolving.

It might be thought that conservation of mass would be more obvious in the case of a physical change than in a chemical reaction (if dissolving is considered a physical change - see above). However, research suggests that learners do not always understand what happens to the solute when it dissolves.[23]

The classroom exercise provided is designed both to elicit students' ideas about what happens to the mass present when a solution is formed, and also to challenge their thinking. The exercise requires students to predict the mass of a liquid and solute (of given masses) when first mixed, and when the solute has dissolved. They are also asked qualitative questions about the examples:

1. Sugar/water: the students are asked to explain where the sugar went when a solution forms.
2. Copper sulfate/water: the students are asked about the colour change (to focus their thinking on a property of the solute now transferred to the solution), and then where the copper sulfate went.
3. Sugar/water: students are now provided with particle diagrams of the solvent and solute, and the resulting mixture, and asked why the liquid tastes sweet (to focus their thinking on both the property of the sugar transferred to the solution, and to provoke them to think about the particle model).
4. Salt/water: students are asked where the salt went.

The design of the probe is intended to help teachers identify 'non-conservers' - pupils who do not realise that the solute is still present in the solution, and therefore its mass is also present - and then challenge these individuals to think about why the 'water' has new properties once the solute is no longer visible.

When this probe was piloted in schools it was found to be effective at diagnosing students who do not appreciate that mass is conserved on forming a solution. Most students know that when a solid is first added to a solvent the weight will increase accordingly. Many students will be aware that the weight of the solute will continue to be registered after the solution is formed:

'It dissolved into the water but was still there so the weight was still there.'

However, a significant proportion of students assume that when the solid is added to a solvent (and can still be seen at the bottom of the beaker) the mass of the solute will register, yet think that once the solid cannot be seen then the weight of the mixture will return to what it was before the solid was added.

This might be seen to be consistent with literature reports that younger students may simply consider the solute to have 'disappeared' once it can no longer be seen.[24] However, when the materials were piloted with 11-13 year old students for this project, it was found that many of the 'non-conservers' were aware that the solute was still present, albeit not visible:

'The sugar dissolved into the water which made it look like the sugar has disappeared.'

'The salt dissolved into the water and is still in there but cannot be seen'

'The copper sulfate dissolved into the water but it hasn't gone anywhere, it just can't be seen'

Clearly, for these students, knowing that the solute is still present does not necessarily imply that its mass will be registered. One explanation for this is simply that these students do not conserve mass, *ie* do not recognise a need for the solute to continue to have mass when not visible - after all if some of its attributes (surface, shape, grain) are no longer perceptible, then perhaps weight similarly 'dissolves' away.

However, responses to the exercise suggest that some of the non-conservers are aware that properties such as taste and colour may be retained ('the sugar has dissolved all in to the water but you can still taste it because there is [sic] millions of sugar particles in the water'; 'it has turned blue because the particles has [sic] spread and you can't see the lumps of it'), and it may be that some students are assuming that the dissolved solute has buoyancy and will not register any weight.[25] (Experience with buoyant objects in baths and swimming pools appearing weightless might suggest this.) Whatever the reason, the exercise does provide an opportunity for teachers to diagnose this belief and challenge it. The questions in this classroom exercise can be readily replicated on a top pan balance to demonstrate that the solute mass continues to register as the solute dissolves.

Chemical stability
'If an atom has been filled up or [is] all ready full up (of 8 outer electrons) it becomes stable and therefore it is unreactive. The atom will stay that way forever and not react or loose or gain any electrons.' Comment of student commencing post-16 chemistry.[26]

Stability (and the related notion of lability) are important ideas in chemistry. The noble gases were formerly called the inert gases (ie the 'not labile' gases), and the stability of noble gas electronic structure is much emphasised at upper secondary level.

The reactivity series of the metals, and the order of reactivity of the halogens are used as key principles for explaining why certain reactions do, or do not, occur. Of course such explanations can readily become tautologies (see Chapter 3) - so we might say that chlorine will displace iodine from its salts because chlorine is more reactive, when we only know that chlorine is more reactive because of our observations of this and other reactions. Nevertheless, stability and reactivity are key ideas in chemistry.

Research suggests that students may often have a limited appreciation of ideas about stability and reactivity. In particular, learners may readily come to adopt ideas about stable electronic structures (ie 'full shells' or 'octets'), but then to focus on this factor to the exclusion of other considerations.

Two of the classroom resources included in the companion volume are designed to help teachers explore their students ideas about 'stability' and chemical reactivity.

Students' ideas about chemical stability

The Chemical stability probes are designed to explore how students judge the relative stability of related chemical species. The original form of this probe - an updated version of which is provided as Chemical stability (1) - used the three species Na, Na^+ and Na^{7-}, and was provoked by the finding that some students considered that the Na^{7-} anion would be stable because it had an octet structure.[27]
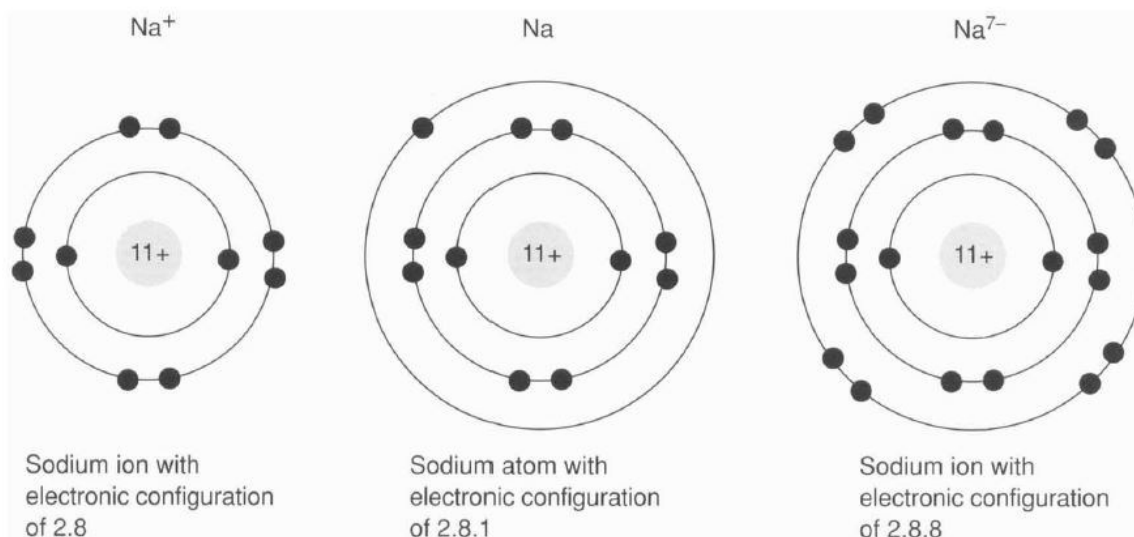

Figure 6.12 Representations of three species presented in Chemical stability 1 probe

The probe was first used with a group of sixteen post-16 students who had studied the topics of atomic structure and ionisation energies at college level. It was found that most (13/16) thought that the Na^+ ion would be more stable than the Na atom. Although the Na^+ species is commonly found as part of chemical systems, in isolation the neutral atom would be considered more stable. The cation would spontaneously attract a free electron, whereas energy is needed to ionise the atom.

Of more concern, over half the group (10/16) thought the neutral atom would be less stable than the Na^{7-} species - a highly charged metal anion. Half of this group also believed that this anion would be as stable as the Na^+ cation. The explanations given were usually in terms of the species with octets or full outer shells being more stable. (Of course Na^{7-} is actually 10 electrons short of a full outer shell, but this point was generally overlooked).

When the probe was given as an induction exercise to new students starting a post-16 chemistry course it was found that similar responses were obtained: 11/13 students thought that both ions would be more stable than the atom, and 9/13 thought that the anion was as stable as the cation.

When the probe was piloted for this project with two classes[28] of 15-16 year olds in a secondary school, it was found that nearly all of students (57/59, ie 97%) thought that the cation was more stable than the atom; and over four-fifth (51/59, ie 86%) though that the neutral atom was less stable than the Na^{7-} anion. Comments from students in this school included;

'[Na^{7-}] has a full outer shell of electrons therefore is more stable. [The Na atom] only has one outer electron and is less stable.'

'[Na^{7-} and Na^+ are equally stable] 'because they both have full outer shells meaning they both do not need to lose or gain electrons'.

A few students even thought that the anion would be more stable than the cation - 'because both have a full outer shell but [Na^{7-}] has more of them so it is more stable'.

The probe has also been presented to student teachers. When 38 postgraduate trainee science teachers undertook the probe most (26/38, ie 68%) thought that the sodium cation was more stable than the atom, and a significant minority (1 5/38, ie 39%) believed that the anion was more stable than the neutral atom.[29] When a small group of Hungarian university students training to be chemistry teachers tried a version of the probe, a number (3/8) thought that the sodium cation was more stable than the atom, and one member of the cohort believed that the anion was more stable than the neutral atom.[30]

Alternative versions of the probe, Chemical stability (2-7), have since been produced with other triads of species for several other elements. All of these are suitable for use in post-1 6 courses, and probes 1-4 are also suitable for students in the 14-16 age range who have a basic appreciation of atomic structure.

When the probes[31] were piloted for the project they revealed that the focus on full electron shells was also found in other examples. The ions C^{4+} and C^{4-} were both judged more stable than a neutral carbon atom, and to be equally as stable as each other, 'because they both have full outer shells of electrons'. Similarly the beryllium atom was considered less stable than the Be^{6-} ion 'due to [Be^{6-}] having complete outer shell' which (according to one student) made it 'very hard to remove electrons' compared to the atom where 'electrons more easily removed'. Again the full shell criterion was seen by some students to have priority over any consideration of electrical neutrality. In one of the probes (probe 6) the Cl^{11-} ion was compared with the chloride ion and the neutral atom. Even such a highly charged species was thought to be more stable than the atom, as it had 'a full shell of outer electrons'.
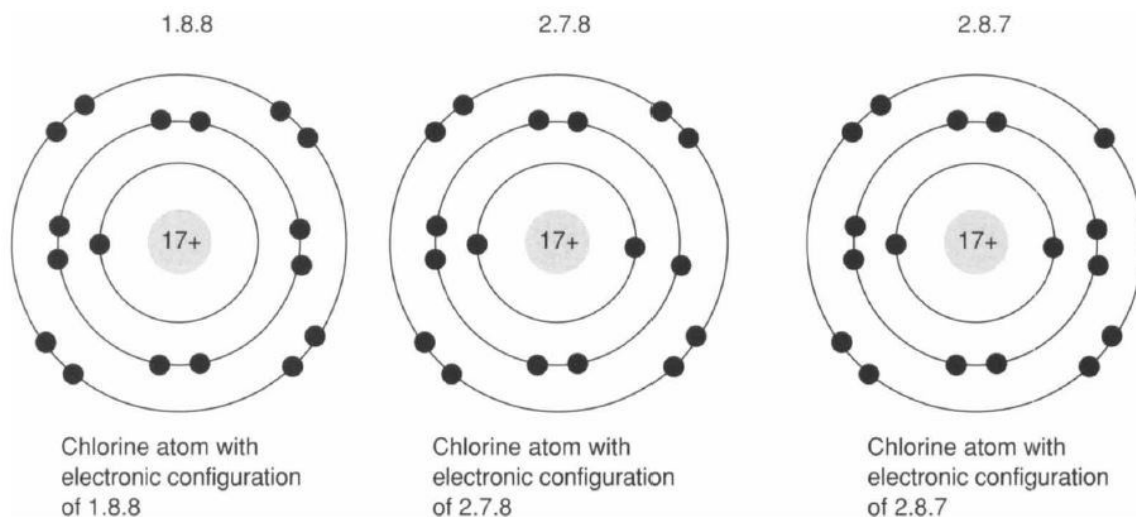
Figure 6.13 Representations of three chlorine atoms presented in the Chemical stability(5) probe

One of the probes (probe 5) takes a slightly different approach, asking students to compare a chlorine atom in the ground state (2.8.7) with two excited atoms of configurations 1.8.8 and 2.7.8 (see Figure 6.1 3).

One student suggested that the 2.8.7 configuration (ground state) atom was less stable than the (more excited, higher energy) option of a 1.8.8 configuration, as the atom with the 2.8.7 configuration 'requires 1 more electron to fill the outer shell unlike [the excited atom.]' A classmate who shared this belief that the ground state atom was less stable because the excited atom had a full [sic] outer shell, also thought that the atom with the 1.8.8 configuration would be more stable than the atom with the 2.7.8 configuration as the 1.8.8 configuration had both 'full outer shell and full second shell'.

In these responses we see that the criteria of a full outer shell can seem even more important to students than an atom having full inner shells. Clearly the 'full outer shell' notion is often used uncritically by students, without any deeper understanding of how it relates to other relevant factors.

Relating stability to reactivity
The Chemical stability probes (discussed above) are intended to allow teachers to see how strong their students adherence to the 'an octet structure is always more stable' rule. This alternative conception would seem to be quite widespread if the responses collected in the pilot are any indication. Whilst the suite of probes does provide teachers with a context in which to challenge this belief, it is an artificial comparison as it does not provide any context for judging the stability of the species.
Teachers clearly need to challenge the beliefs that lead to students arguing that Na^{7-} is a more stable species than Na^+. However, although it is interesting that many students consider the sodium cation to be more stable than the atom (despite the ionisation of the atom being an endothermic process), this is not such a surprising finding when the sodium ion, unlike the atom, is found as part of familiar stable systems.
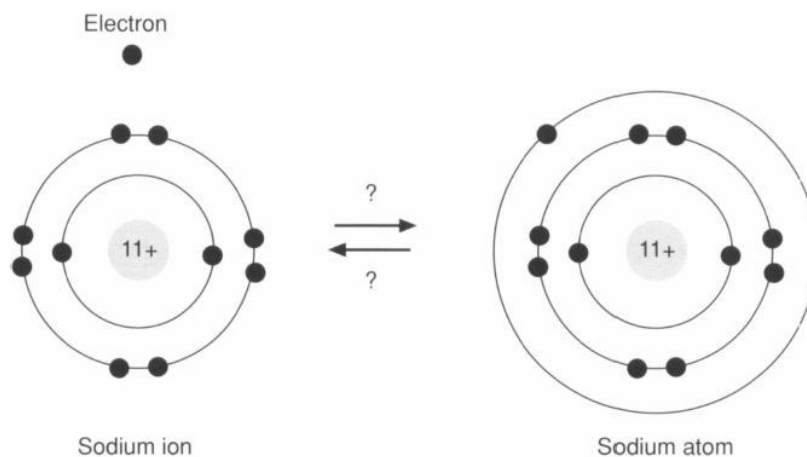
Figure 6.14 Two possible processes

The Stability and reactivity probe takes this comparison and places it in a context. Students are presented with a diagram (see Figure 6.1 4) which shows the possible processes of the atom being ionised to give a cation and an electron, and the cation joining with an electron to form an atom. The ionisation process requires an energy input, and will not occur spontaneously, whereas the positively charged ion and negative charged electron will spontaneously form an atom.

In the Stability and reactivity probe students are asked which of the two processes are likely to occur, along with questions about which of the ion and atom are (a) more stable, and (b) more reactive.

If students recognise that the electrical attraction will lead to the formation of the atom, but ionisation is not spontaneous, then the usual meanings of 'stable' and 'reactive' should lead to them judging the atom as more stable and the ion as the more reactive species in this context.

When the probe was piloted in schools and colleges it was found that students often held the alternative conception (that ion formation would be spontaneous) and for some students the response patterns were not so clear cut.

In one school over fifty 14-15 year old students responded to the probe. 43/54 students (ie 80%) thought the atom would emit an electron, and only one thought the atom and electron would combine. (Seven students did not think either process would occur, and three responded that they did not know the answer.) As one of the students explained: 'The sodium atom will emit an electron because it wants to have a full outer shell.' In this case there was some consistency, with most students considering the ion more stable and the atom more reactive.

This pattern of responses was also found among many post-16 students. One student in a group of 16-17 year olds in another school explained her responses thus:

'[The sodium ion is more stable than the sodium atom.] This is because the sodium ion has more of a full outer shell than the sodium atom.'

'[The sodium atom will emit an electron to become an ion.] To achieve stability by having a full outer shell.'

'[The sodium atom is more reactive than the sodium ion.] It has less of a full outer shell.'

However, many students do not produce responses which are consistent. For example, another student in the same group judged the ion to be both the more stable, and the more reactive of the species:

'[The sodium ion is more stable than the sodium atom.] The atom loses an electron to give it a full outer shell of electrons.'

'[The sodium ion is more reactive than the sodium atom.] Since the sodium ion has a positive charge it will readily attract electrons from another substance therefore reacting with that substance.'

A small group of 13-15 year old High School students in Greece also responded to the probe. Most thought that the sodium ion was more stable than the atom (5/6, with 1/6 considering the atom more stable), and that the sodium atom was more reactive than the ion (4/6, with 1/6 believing the ion more reactive, and 1/6 unsure). All of the small group thought that the atom would spontaneously emit an electron.

When the small group of Hungarian university students training to be chemistry teachers attempted this probe they were divided over which process would spontaneously occur. Three of the eight in the group thought the cation and electron would join, an equal number expected the atom to spontaneously emit the electron, and the other students did not think either process would occur.

Perhaps part of the problem here is that students have understandable difficulty in considering the 'reactivity' of a chemical species in isolation: reactivity needs to be judged in a realistic chemical context. As discussed earlier in the chapter, students often tend to muddle ideas at the level of macroscopic phenomena and our molecular models (eg see Figure 6.11). Indeed, it has been suggested that to help students appreciate this distinction the word 'react' should be reserved for the macroscopic process, and the alternative term 'quantact' used to describe the molecular interactions that occur during a reaction (see Figure 6.1 5).[32,33]
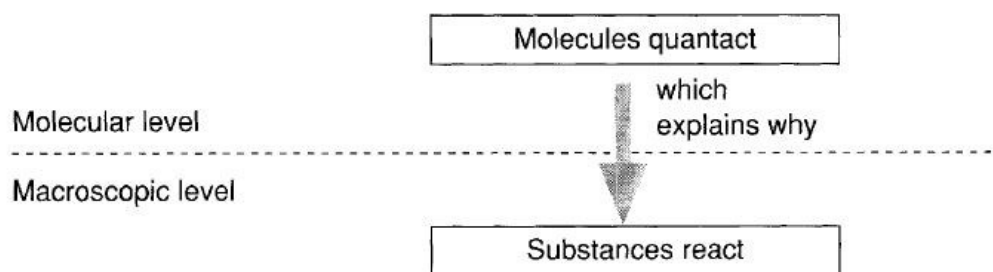
Figure 6.15 Quantaction and reaction

This terminology is not yet in common usage, but could help teachers maintain the distinction between the macroscopic level of observable phenomena, and the explanatory framework of the molecule model. If this suggestion is followed, then just as molecular level particles should not be said to melt during melting, or expand during thermal expansion, nor should they be said to react during reaction. The particles quantact, and this quantaction at the molecular level can be used to explain why reaction occurs at the macroscopic level.[34]

Notes and references for Chapter 6

1. P. Gailiunas, Is energy a thing? Some misleading aspects of scientific language, School Science Review, 1988, 69 (248), 587-590.

2. M. T. H. Chi, j. D. Slotta, & N. de Leeuw, From things to processes; a theory of conceptual change for learning science concepts, Learning and Instruction, 1994, 4, 27-43.

3. A. Brook & R. Driver, in collaboration with D. Hind, Progression in Science: The Development of Pupils' Understanding of Physical Characteristics of Air across the age range 5-1 6 years, Leeds: Centre for Studies in Science and Mathematics Education, University of Leeds, 1989.

4. P. Johnson, Children's understanding of substances, part 1 : recognising chemical change, international journal of Science Education, 2000, 22 (7)7,1 9-737.

5. K. S. Taber, Finding the optimum level of simplification: the case of teaching about heat and temperature, Physics Education, 2000, 35 (5), 320-325.

6. Of course this approach needs to be extended to ionic materials, where a compound will contain two or more types of ion rather than one type of molecule. Hydrated salts are usually considered as single substances despite being comprised of several types of ion and molecules of water. As was pointed out in Chapter 2, the basic concepts of chemistry are far from straightforward.

7. The original student statement was that a 'Compound is one or more elements mixed together': K. S. Taber, Chlorine is an oxide, heat causes molecules to melt, and sodium reacts badly in chlorine: a survey of the background knowledge of one A level chemistry class, School Science Review, 1996, 78 (282), 39-48.

8. Research suggests that students tend to see science as largely about facts, and to have naïve notions of how and why models are used in science (see notes 9 and 10). This situation seems to have persisted despite being raised as an issue twenty years ago (see notes 11 and 12).

9. P. Driver, J. Leach, R. Millar & P. Scott, Young People's Images of Science, Buckingham: Open University Press, 1996.

10. L. Grosslight, C. Unger, E. Jay & C. L. Smith, Understanding models and their use in science: conceptions of middle and high school students and experts, journal of Research in Science Teaching, 1991, 28 (9), 799-822.

11. R. J. Osborne & J. K. Gilbert, The use of models in science teaching, School Science Review, 1980, 62 (218), 57-67.

12. N. J. Selley, The place of alternative models in school science, School Science Review, 1981, 63 (223), 252-259.

13. P. Johnson, Progression in children's understanding of a 'basic' particle theory: a longitudinal study, International journal of Science Education, 1998, 20 (4), 393-41 2.

14. M. R. Abraham, E. Grzybowski, J. Renner, J. & E. Marek, Understanding and misunderstanding of eight grades of five chemistry concepts found in textbooks. journal of Research in Science Teaching, 1992, 29 (2), 105-1 20.

15. T. Wightman, in collaboration with P. Green and P. Scott, The Construction of Meaning and Conceptual Change in Classroom Settings: Case Studies on the Particulate Nature of Matter, Leeds: Centre for Studies in Science and Mathematics Education, 1986, 21 7.

16. As one student explained 'it would seem a bit of an odd-ball' for one atom to have another atom's electron: K. S. Taber, An alternative conceptual framework from chemistry education, International Journal of Science Education, 1998, 20 (51, 597-608.

17. The student was undertaking an induction exercise at the start of an A level (UK) chemistry course. The two definitions which are discussed in the rest of this section had the same group as their source. For a discussion of suitable induction tasks at this level, and likely student responses, see K. S. Taber, Chlorine is an oxide, heat causes molecules to melt, and sodium reacts badly in chlorine: a survey of the background knowledge of one A level chemistry class, School Science Review, 1996, 78 (2821, 39-48.

18. L. Renstrom, B. Anderson, and F. Marton, Students' conceptions of matter, journal of Educational Psychology, 1990, 82 (3), 555-569.

19. During the piloting of the resource materials Elements, compounds and mixtures one of the teachers commented on how students in his class of 16 year olds 'wanted to see bonds as concrete structures, ie lines between cores'.

20. Figures 6.7 and 6.8 adapted from K. S. Taber, Molar and molecular conceptions of research into learning chemistry: towards a synthesis, 2000 - available via Education-line, at http://www.leeds.ac.uk/educol/ (accessed October 2001).

21. P. Johnson, Children's understanding of changes of state involving the gas state, part 1: Boiling water and the particle theory, International journal of Science Education, 1998, 20 (5), 567-583.

22. Qualifications and Curriculum Authority (QCA), Standards at Key Stage 3 Science, London: QCA, 2001.

23. A. K. Griffiths, A critical analysis and synthesis of research on students' chemistry misconceptions, in H-J. Schmidt, Proceedings of the 1994 international Symposium Problem Solving and Misconceptions in Chemistry and Physics, ICASE [The international Council of Associations for Science Education] Publications, 1994, 70-99.

24. M. Slone & F. D. Bokhurst, Children's understanding of sugar water solutions, International journal ofscience Education, 1992, 14 (2), 221-235.

25. This possibility has been suggested by Prof. Robin Millar of York University, based on related research undertaken in the science education group at York.

26. K S. Taber, An alternative conceptual framework from chemistry education, International journal of Science Education, 1998, 20 (5), 597-608.

27. K. S. Taber, Case studies and generalisability - grounded theory and research in science education, International journal of Science Education, 2000, 22 (S), 469-487.

28. The result from the top two ability sets are discussed. Although a third set also undertook the exercise it was found that their answers revealed a lack of the basis understanding of atomic structure which was needed to make any sense of the probe.

29. K. S. Taber, Trainee Science Teachers' Conceptions of Chemical Stability, 2000 – available via Education-line, at http://www.leeds.ac.uk/educol/ (accessed October 2001).

30. This data was collected by Prof. ZoltAn Toth of the Chemical Methodology Group at the University of Debrecen, Hungary.

31. Five probes were piloted. Two more (probes 2 and 7) were added to the set during the process of revising materials for publication.

32. K. S. Taber, The campaign to stop molecules reacting, Education in Chemistry, 2001, 38 (1), 28.

33. Figure 6.1 5 adapted from K. S. Taber, Building the structural concepts of chemistry: some considerations from educational research, Chemistry Education: Research and Practice in Europe, 2001, 2 (2), 1 23-1 58, available at http://www.uoi.gr/conf-sem/cerapie/ (accessed October 2001).

34. The term 'interact' is too general, as it can apply to elastic collisions between molecules, and intermolecular bonding formation (both without reaction) as well as quantaction (leading to reaction).