From:
Taber, K. S. (2002).
Chemical Misconceptions - Prevention, Diagnosis and Cure: Theoretical background (Vol. 1).
London: Royal Society of Chemistry.

RS•C

# 2. Concepts in chemistry

**This chapter discusses the nature of chemical concepts and how such concepts are learnt. The problem of clearly defining key chemical concepts such as 'element' and 'molecule' is explored, and the implications for teaching are considered.**

## What are chemical concepts – and why are they hard to learn?

The term 'concept' is used a lot when talking about learning, but it is one of those words – perhaps like 'molecule' (see below) – which although we seem to know what we mean by it, is not so easy to define precisely.

Psychologists refer to the ways in which we represent our knowledge as 'schema', and concepts (or categories) are important types of schema for making sense of our world.[1] A concept is just a way of breaking up the world into bits that we can recognise, and think about. Some of our concepts – so called identity concepts – refer to specifics such as your particular school or college, or particular people. I am writing this at a place I recognise as the University of London Institute of Education. I have a mental representation – a concept – of that institution. Other types of concept – so called equivalence concepts – do not refer to specific items, but to categories that may have several, or even many, members. It is these types of concepts that are important in learning science.

Even among these categories there are important distinctions. Some concepts are ad hoc – *ie* they are made up as we go along for a particular purpose (such as the group of students who have failed to bring the homework and who have been asked to remain at the end of today's class). More significant for our present purposes are natural concepts and rule-governed concepts.

People the world over tend to categorise certain things in the same ways. For example we all use categories such as 'tree' without having to think about how such terms are defined – we think we know what a tree is when we come across one! These concepts seem to be largely intuitive – we do not seem to need to be taught the concept. We may teach a young child the word 'tree' but somehow she will learn what is, and what is not, considered a tree without either being given a detailed definition, or having to be taken through large numbers of examples of trees and non-trees. We say that the child recognises a 'family resemblance' between objects considered as trees.[2] This is an important point that is not always recognised by teachers – although students often seem to have great difficulty in learning aspects of science regardless of well structured teaching, those same students somehow learn to use natural categories with only a minimal and often unplanned opportunistic 'teaching' input. This suggests that the brain is 'programmed' to be 'ready' for such instruction.[3]

Now this is obviously not supernatural: rather, through millennia human brains have evolved to be predisposed to recognise the types of categories which are useful to survival. Although this makes some types of learning much easier, it can also be a nuisance in formal education.

This is because, in science, we are largely dealing with rule-governed rather than natural concepts. In other words we often define new concepts.[4] Unfortunately some scientific definitions may seem to be inconsistent with natural ones.[5] For example, in science we have a concept of 'animal' which includes a wide range of living things such as various types of worms, fish, birds, insects etc. Yet there is also a natural category of living things limited to large mammals such as horses, cows, pigs, deer etc (and not including humans) which are commonly described as 'animals' in everyday life. Insects are not considered animals in this sense. Spiders – which according to science are animals and are not insects – are usually considered as insects, but not animals.

It is difficult to overcome this problem for a number of reasons. The natural category meanings are usually learnt before the scientific ones, and are very commonly used in everyday life (and so get reinforced regularly). Their 'lifeworld' (everyday) meanings for words such as 'animal' are useful in

RS•C

many contexts, therefore it is difficult to expect students to give them up. Also they are different types of concepts – and so they are difficult to fully reconcile. Natural categories are not defined by any 'hard and fast' rules, and may have very fuzzy boundaries (so today my hamster will be an animal as we are talking about animals as pets, but tomorrow when we talk about animals as animals in the wild…), whereas in science we (usually) use rules to define our concepts.

In chemistry these problems may seen less extreme than in biology, or physics (where most of the key concepts are blighted by having labels which are also used in more vague everyday senses: 'energy', 'momentum', 'force', 'impetus', 'work'…[6]), but we may still find students using words like 'natural', 'synthetic', 'metal' 'pure' and 'substance' in ways which do not match the technical meanings. [7]

We might expect that learning about chemical concepts which do not have everyday counterparts – such as electron, reducing agent and hybridised atomic orbital – will not trigger the same problems. Yet we all know that students do have difficulties acquiring such concepts. Perhaps the problem is that the structure of our brains has evolved to be inherently good at learning natural concepts (by a kind of cultural osmosis with feedback), but are less well suited (adapted) to learning the type of rule-based concepts so important in science.

## Forming concepts – noticing similarities and differences

In one sense a person can be said to have acquired a concept once they are able to identify examples, and distinguish them from non-examples. This may be the case whether the concept concerned is that of 'cat' or 'cation'. Acquiring and using concepts therefore requires the learner to recognise similarities and differences.

For example, consider the two figures below (Figure 2.1 and Figure 2.2).

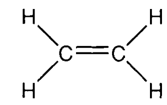


**Figure 2.1 A molecule**

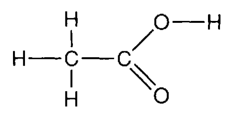


**Figure 2.2 A (different) molecule**

A student may recognise that they are both examples of molecules (if they have a concept of molecule), and perhaps that they are both molecules of substances considered organic (if...). The student might identify that both compounds include a double bond (if...). Perhaps the student could identify the first as an example of a hydrocarbon (if...), and further as an alkene (if...) and even as ethene (if...); and the second as a carboxylic acid (if...), and perhaps as ethanoic acid (if...). Making these classifications requires the students to recognise certain attributes of the species represented as pertinent to these various concepts.

One way to focus students' thinking on the relevant attributes is to ask them to spot similarities and differences (*eg* between diagrams such as those above). An approach that has been used in educational research is to present learners with three diagrams, and ask them to (a) suggest which is the odd-one-out and (b) explain why. This method requires the student to make discriminations between the diagrams, and so elicits the features (the 'constructs') they bring to mind when thinking

RS•C

about the diagrams. This approach, known as 'Kelly's triads' can produce some interesting suggestions, and may reveal both areas of ignorance (when students fail to spot 'obvious' chemical similarities and differences) and alternative conceptions.

Such an approach can allow the teacher to explore the student's inventory of chemical constructs (by working through a series of comparisons with different 'triads' of diagrams). When this techniques was used with some post-16 students who were presented with triads showing various combinations of molecules, atoms, ions etc, it was possible to develop a simple framework for the types of comparisons these students made.[8]

The four main classes of suggestions from students concerned aspects of the structure of the chemical species; comments about the properties of the species or the substance it was a component part of; classification of the species (or the substance it was a component part of) in various chemical categories; and aspects of the way the species was represented in the particular diagram used.

By matching the constructs used by individual students to this framework it is possible to get an impression of the types of features that a particular student focuses on.

Consider the set of constructs elicited from two classmates, Kabul and Rhea, when they undertook the exercise during their first term of post-16 chemistry. (In these schemes the normal text represents the framework developed from all the responses, and the bold print shows the constructs used by the individual students). Kabul, who went on to be very successful in the course, uses a range of ways of discriminating chemical species from the four main categories.

RS•C

**Kabul's constructs:**

- structural:
  - molecular:
    - shape: **tetrahedral arrangement**
    - others:
  - sub-atomic:
    - nuclear:
    - electronic:
      - c.f. noble gas electronic configuration: **possess octet state**
      - others:
  - crystal: **lattice arrangement**
  - bond type: **covalent bonding; bond between different elements; ionic compound; bond between non-metals; polar covalent bond**
  - includes:
- properties:
  - chemical:
    - reactivity: **can undergo reaction; can undergo reaction to form ionic bonds; cannot exist on its own; high reactivity; stable**
    - specific: **forms diatoms; displacement of hydrogen by reactive metals; can undergo combustion**
    - valency: **electrovalency of -2; covalency of 4; electrovalency of 1**
  - physical:
    - macroscopic: **low melting point; soluble in organic solvents; conduction of electricity; soluble in water**
    - molecular: **high energy required to break bonds**
      - charge: **charged particle; a gain of electrons; ionising slowly**
      - others:
    - environmental:
- classification:
  - periodic table:
    - electronegativity: **metal**
    - block:
    - period:
    - group: **found in group 7; found in group 1; found in group 8**
  - state: **state of existence is solid**
  - reagent type:
  - microscopic species: **represents an ion**
  - type of substance: **only one element; organic substance; compound**
  - specific substance:
  - occurrence:
- diagrammatic features: **we can know the period; represents a type of bond**
- ambiguous/miscellaneous: **can be present in a noble gas; ionisation**

However, classmate Rhea made many fewer chemically significant discriminations, and indeed often seemed to largely focus on such graphical conventions as whether electrons were represented as 'e', 'e$^-$' or '•'. Rhea later decided not to continue with her study of chemistry, but to concentrate on her other academic subjects.

RS•C

**Rhea's constructs:**

structural:
- molecular:
  - shape: **symmetrical-ish; circular**
  - others: **two joined together; all clumped together**
- sub-atomic:
  - nuclear: **got a 17+ charge in the middle**
  - electronic:
    - c.f. noble gas electronic configuration: **one electron short of a full outer shell; full outer shell**
    - others: **three shells**
- crystal:
- bond type: **double bonds drawn in**
- includes: **got orbitals; got 'H's; two different elements in them**

properties:
- chemical:
  - reactivity:
  - specific:
  - valency:
- physical:
  - macroscopic:
  - molecular:
    - charge:
    - others:
  - environmental:

classification:
- periodic table:
  - electronegativity:
  - block:
  - period:
  - group:
- state:
- reagent type:
- microscopic species:
- type of substance:
- specific substance:
- occurrence:

diagrammatic features: **other shells drawn in ; electrons as circles; electrons as 'e's; say what they are; minus signs on some of the 'e's; got shading; got brackets; written; got plus signs; say how many electrons are shared; got plus signs in the middle; got charges drawn in; 3-D drawing; simple sketch drawing; got a key**

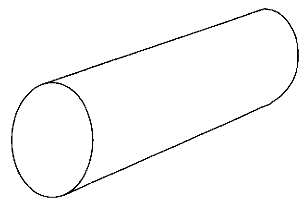
ambiguous/miscellaneous: **got structure(s)**

The Kelly's triads technique is usually used on a one-to-one basis, but can be adapted for class use. An alternative approach for the classroom, however, is to ask students to suggest similarities and differences between two diagrams (or other suitable stimuli).[9]

One of the resources included in this publication is a set of probes using such dyads (pairs) of pictures, **Chemical comparisons**. There is an almost unlimited possibility for developing questions with various dyads, and so the specific probes included should be seen as exemplars.

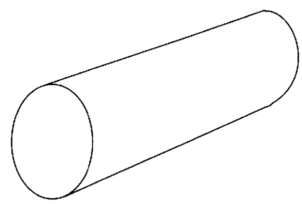
Some of these examples are suitable for use with 11–14 year olds. For example Figures 2.3 and 2.4 show cylinders labelled as iron and sulfur.

RS•C



Iron

**Figure 2.3 A picture of iron presented to students**



Sulfur

**Figure 2.4 A picture of sulfur presented to students**

Responses to such dyads are able to demonstrate significant differences between the repertoires of ideas that students call upon in making comparisons. One student in a group of 13–14 year olds suggested four similarities in this example: 'they are both solids', 'they are both elements', 'they are both in rods' and 'they are the same size'. This student indicated that the former two suggestions, but not the latter two were important to chemists. The same student suggested five differences: iron being a metal, colour, iron being malleable, poor versus good conductor, iron being ductile (and she thought that all but colour were significant differences). On this same question another student in the group was only able to suggest that 'they are both the same shape & size'.

Within the group of students there were a wide range of suggestions, many of which were valid (see Table 2.1). Some of the suggestions students make can reveal alternative conceptions (such as believing iron is found native), and the sophistication of answers can vary. However, this latter point should not be considered as a draw-back. As an open-ended activity this technique allows 'differentiation by outcome'. In other words, lower attainers should be able to contribute ideas, whilst there is scope for the most able to think up suggestions related to a wide range of relevant chemical themes.

RS•C

| | Similarities | Differences |
|---|---|---|
| Acceptable | Same shape/cylindrical/rods<br>Same size<br>Elements<br>Both appear on the Periodic Table<br>Both combine with other things<br>Both react with oxygen<br>Solid at room temperature | Conductivity (electrical)<br>Conductivity (thermal)<br>Density<br>Weight<br>Boiling temperature<br>Melting temperature<br>Metal/non-metal<br>Magnetic<br>Silver-grey/ yellow<br>Hard/powdery<br>Malleability<br>Ductility<br>Ease of cutting up<br>Iron rusts<br>Feel different<br>'Shineness' |
| Dubious | Colour<br>Both natural solids (minerals)<br>Don't look malleable<br>Have the same molecules set-up<br>Appear to have the same mass<br>Exactly same smoothness | Sulfur is more reactive |

**Table 2.1 Comparisons between iron-sulfur dyad by students in one class**

Many of the probes included in the resource use diagrams of molecular level systems, rather than diagrams of macroscopic samples. For example, Figures 2.5 and 2.6 show a dyad representing solid and aqueous sodium chloride.

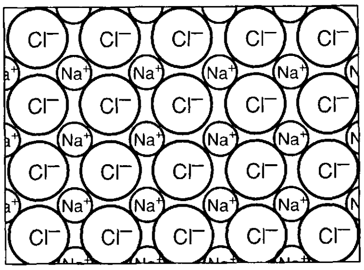



**Figure 2.5 A representation of solid sodium chloride NaCl presented to students**

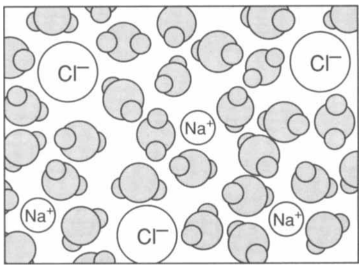



**Figure 2.6 A representation of sodium chloride solution presented to students**

RS•C

This dyad was intended primarily for students in the 14–16 age range, but was attempted by some students in the group of 13–14 year olds. Their suggestions are given in Table 2.2. Although they made some valid observations (about the balance between positive and negative charge, and the difference in the order of the arrangements), there was also evidence of some confusion over basic ideas. For example, it was suggested that the ionic solid was a mixture, and that the solution was a gas (perhaps because the ions themselves appeared quite spread out). Clearly this exercise can lead to useful discussion points.

| | **Similarities** | **Differences** |
|---|---|---|
| Acceptable | Both contain $Na^+$ and $Cl^-$<br>Same amount of $Na^+$ and $Cl^-$<br>Same amount of positive and negative ions | Not joined similarly<br>Evenly spread – randomly spread<br>Compound – mixture |
| Dubious | Both represent mixtures<br>They're both compounds<br>Same substance in different states | One is a solid and one is a gas |

**Table 2.2 Comparisons between solid and aqueous sodium chloride made by students in one class**

As students learn more chemistry it is possible to ask them to make more complex or subtle comparisons. So many of the probes included in this resource are intended primarily for students on post-16 courses. The exercise was carried out with a group of 17–18 year olds nearing the end of their chemistry course. These students were able to suggest many comparisons that would not have been possible for the younger students. For example, one student compared a dyad representing $NH_3$ and $BCl_3$ (Figures 2.7 and 2.8).

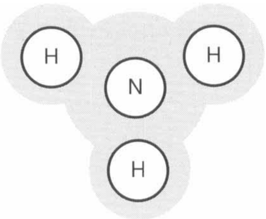



**Figure 2.7 A representation of an ammonia molecule**

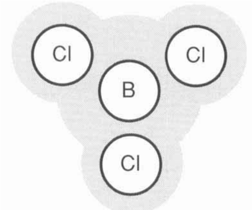



**Figure 2.8 A representation of a boron trichloride molecule**

The student identified a number of valid differences between these superficially similar species: tendency to dimerise ($BCl_3$), state (gas – solid), electron deficient nature ($BCl_3$) and bonding character. However, in the last case the bonds were described as covalent ($NH_3$) and ionic ($BCl_3$), suggesting

RS•C

that the student should be encouraged to think in terms of the extent of bond polarity rather than in absolute terms (see Chapter 8).

The examples discussed here have shown how the simple technique of asking students to spot similarities and differences can be useful for auditing knowledge and spotting alternative conceptions, as well as providing some variety through an open-ended activity. A similar approach may be used to explore analogies used in teaching. When introducing difficult ideas, which do not have any obvious 'anchors' into students' existing experiences, it can be useful to use analogies to help students make sense of the unfamiliar material (see Chapter 4). However, analogies can also lead to inappropriate and wrong learning unless students are very clear about which features of the analogue they are meant to adopt (see Chapters 7 and 10).

One example of a teaching analogy that is sometimes used is that of the atom being like a tiny solar system. Although this can be useful, it can also lead to students making incorrect assumptions about atoms (either due to a poor understanding of solar systems, or due to an over-zealous adoption of the comparison). The approach used in the **Chemical comparisons** resource has also been adopted in another probe to explore whether students appreciate the atom-solar system analogy. The details of that probe, and how students respond to it, are given in Chapter 7, but it is worth noting here that teachers could adopt the approach used here when using their own teaching analogies or if concerned about the analogies that students may bring to class. The **Chemical comparisons** probes may be readily adapted by replacing the diagrams with any others the teacher may wish to use – for example, pictures of the π-cloud in benzene and a doughnut – if this is an analogy used with students.

The technique of focusing on similarities and differences can also be useful in responding to specific problems students may have in making scientific discriminations. One learning difficulty that has been reported in chemistry is that of not distinguishing between strong acids and concentrated acids. It is understandable that students might see these terms as synonymous, as in everyday life a concentrated solution is often described as a 'strong' solution, whereas in chemistry acidic solutions may be weak and concentrated or strong and dilute (as well as strong and concentrated and weak and dilute). Included in the companion volume is a classroom probe, **Explaining acid strength**, which allows teachers to diagnose whether their students are clear about the distinction between acid strength and concentration. This is accompanied by a classroom exercise, **Classifying acid solutions**, which presents a set of diagrams to help support students making the discrimination. The exercise presents diagrams of acid solutions which vary along the two dimensions (strong-weak and dilute-concentrated), and students are encouraged to focus on the pertinent attributes when comparing the figures (*ie* the amount of solute present in the solution, and the presence or absence of associated solute molecules as well as ions). In this way they are led to classify each diagram as strong/weak and dilute/concentrated. When these materials were piloted for the project it was found that students were generally comfortable in applying the ideas, and that those who had been unclear found the exercises helpful.

## Learning rule-based concepts

In principle it might sound easy to teach rule-based concepts. A sensible approach would be:

- Provide the learner with the rules for, or the definition of, the concept;
- Give a few salient examples, and non-examples, and make sure the learner understands why they are, or are not, examples of the concept;
- Provide practice exercises with plenty of examples and non-examples; and
- Require the learner to be explicit about their reasoning in working through the exercises.

Although such an approach would seem a very sensible way of making sure that students have grasped important new concepts you introduce, it is not foolproof.

RS•C

For one thing, many concepts are more complicated than they may at first appear. This means that making the 'rules' explicit can get tricky. It may be difficult to provide definitions that are both comprehensive and accurate. Definitions that meet these requirements, and are also accessible to learners may be very hard to find. (Some examples of definitions of basic chemical terms are discussed below.)

A second complication is that our definitions use language, and this introduces two more problems. Some students are not easily able to understand complicated sentences.[10] Even when this is not an issue, many of the words used in a definition are themselves labels for other concepts that also need to be understood. If we were to define an alkene as a type of hydrocarbon with a double bond we are assuming that the learner already has an acceptable understanding of both the concepts of 'hydrocarbon' and 'double bond'.

## Providing clear definitions

Unfortunately, many chemical concepts are only 'simple' once they are understood as part of a much wider network of ideas. (The importance of appreciating the way concepts are related is discussed in Chapter 3.) So consider the following definition:

An alcohol is a compound with an –OH group.

This definition would include ethanol etc, but could also apply to ethanoic acid, and even sulfuric acid – which are not considered alcohols. So we would need to add something about the alcohol being an *organic* compound and the –OH group not being part of a larger –COOH group (or an –OOH group for that matter).

If we defined an alkene as having an empirical formula of $C_nH_{2n}$, then we would need to add the proviso that it was not a cyclic molecule (in which case $C_nH_{2n}$ would be an alkane, and the alkene would be $C_nH_{2n-2}$).

Sometimes we can avoid such complications by only providing a limited definition initially, because we only wish to use the definition (and therefore the concept) in a limited range of cases. If learners do not yet know about the existence of cyclic compounds, then they should not misapply the $C_nH_{2n}$ = alkene rule to cyclic alkanes. However, even here we may be storing up problems for the future if we are not careful. For example, if we were to define oxidation as 'the addition of oxygen', we may later wish to add a new 'or the removal of hydrogen', and then later add 'or the loss of an electron', and then even later add 'or an increase in oxidation state'.

There is a real issue here of finding the optimum level of simplification, of balancing the need to keep things simple now, and providing learners with ideas which we are not going to expect them to alter later.[11] Learners do not always find it easy to adjust meanings for technical words once they are acquired. It could be argued that science is largely about culturally agreed models that scientists use to make sense of the world.[12] Moreover, scientists see models as tools: they are usually limited (which means we have to sometimes switch to a different tool), and they are for our benefit (which means we are able to play with them, and even change or discard them). Yet students tends to see our scientific models as simple descriptions of the way nature is. Even when scientific ideas are seen as models, we must remember that – for most students – models are expected to be incomplete copies of nature – rather than convenient abstractions (see Chapter 6).

As teachers we should remember that although there are things in the world which are (by our definitions) oxidising agents or alkalis – the categories themselves are artificial and just for our convenience. For example, acids occur in nature – the idea of 'acid' only exists in our minds. We should also remember that most of these concepts are recent human inventions, and their meanings have changed during the development of science. If we can encourage our students to understand this, then they may find it less stressful when we suddenly expect them to accept bonds that are 'in-between' covalent and ionic (see Chapter 8), or an acid that does not contain hydrogen (*eg* $SbF_5$).

RS•C

## Defining key concepts in chemistry

It is useful to illustrate the problems associated with defining chemical concepts, and so we will consider a small number of the key concepts in chemistry as examples.

Elements and compounds: two of the central concepts in chemistry (see Chapter 6) are 'element' and 'compound'.

Atoms and molecules: the importance of the particle model to making sense of chemistry is well recognised (see Chapter 6), and the concepts of 'atom' and 'molecule' are widely used in the subject at all levels.

Chemical and physical changes: chemistry is largely concerned with the properties and reactions of substances. Properties are often classed as physical (colour, melting temperature...) and chemical (which substances are reacted with, under what conditions, to give which products). Reactions, chemical changes, are a central part of the subject (see Chapter 9). An understanding and application of the distinction between physical and chemical changes is often expected of students at lower secondary level. [13]

It is reasonable to suggest that;

**(a)** it is difficult to form a detailed appreciation of chemistry without a fair understanding of what is meant by these terms; and

**(b)** practising chemists, and chemistry teachers would have a clear understanding of what these ideas mean.

It might be expected, therefore, that school textbooks, and other reference books, would provide consistent, unproblematic, definitions for such key terms (element, compound, atom, molecule, physical and chemical change) and that chemistry teachers would tend to agree on these definitions. However, in practice, this may not be so.

## Elements and compounds

Consider two definitions of the term 'element' from chemistry textbooks aimed at the secondary level:

'An element is a substance which cannot be split up into simpler substances.'[14]

'A substance that is made of only one kind of atom.' [15]

These are very different definitions, one working at the macroscopic level and one at the molecular level (see Chapter 6), but both are common ways of defining the element concept. To the chemist it is clear how these definitions relate to each other, but to a novice they may seem to have little in common. Similarly, the following definitions of 'compound' also seem to be quite distinct:

'A substance consisting of atoms of different elements joined together.'[16]

'A chemical substance made up of two or more elements bonded together, so that they cannot be separated by physical means.' [17]

'A product which has properties different from those of either of the component substances and which is formed with an accompanying energy change is called a compound.' [18]

It is valuable to consider the usefulness of these concepts, to see what lessons can be drawn for teaching using definitions of such central ideas. A classroom exercise, **Definitions**, to explore student reactions to definitions of basic terms is included in the companion volume. Students are asked about the accuracy and usefulness of a set of definitions of key terms (see Chapter 6). Some practising science teachers were also asked about these definitions, and some of their comments are quite illuminating.[19]

RS•C

*An element is a substance which cannot be split up into simpler substances.*

This definition requires the learner to appreciate the chemist's meaning of substance, and also to share what is meant by 'simpler' in this context. One could object that 'simple' here means an element compared with the more complex 'compounds' (and so the definition is circular).

One teacher considered this definition was 'wrong', but still 'helpful' for 13 year olds 'when they have not been taught' about protons, neutrons and electrons. Another teacher judged this definition as 'correct' but 'not helpful' as it was 'too vague'.

A teacher who thought the definition was correct explained that 'anything simpler would not be a substance'.

Another teacher thought this definition was 'wrong' and 'not helpful' as it 'needs to have 'by chemical means' added [as] CERN etc split atoms into more fundamental particles'. Yet this seems to confuse the macroscopic and molecular levels of analysis (see Chapter 6) as atoms do not directly relate to substances.

*[An element is] a substance that is made of only one kind of atom.*

This sounds quite straightforward, but even if students understand about atoms, they also need to appreciate the specific way in which 'one kind' is used – so that atoms with the same mass number but different atomic number of are different kinds, but atoms with the same atomic number and different mass number count as being of the same kind in this context. One teacher judged this definition as both 'correct' and 'wrong': considering it correct until 'you introduce isotopes', but thought this was a helpful definition 'at Year 10 level' [*ie* about 14 years of age]. Another teacher judged this definition as 'correct' and 'helpful' as 'it's simple and straightforward – you can also draw it & represent it visually'. Another thought 'the definition is only really useful when accompanied with plenty of examples'.

*[A compound is] a substance consisting of atoms of different elements joined together.*

One objection to this definition is that it would not include ionic materials, which do not consist of atoms (see Chapter 7). As one teacher commented, this is a 'common definition but causes problems in ionic bonding'. Yet some teachers felt this was an accurate definition. One teacher, who thought this was both 'correct' and 'helpful' thought it was 'easy to represent diagramatically'. Another teacher suggested that this was correct, although not necessarily helpful as a 'knowledge of 'atom' and 'element' [was] required' before it could be applied.

One teacher suggested that the accuracy of the definition depended upon how 'join' was defined, and another who also felt this was 'too vague', and should be 'chemically combined' or 'chemically bonded'.

*[A compound is] a chemical substance made up of two or more elements bonded together, so that they cannot be separated by physical means.*

This definition clearly requires students to already understand the idea of element, and to appreciate what is meant by 'physical means' – it 'depends upon pupils' understanding of physical & chemical change' – (see below) and 'bonded'.

One teacher thought this was a 'correct' definition, but 'not helpful' as it had 'too much detail'. Another teacher thought this was a 'helpful' definition, but 'only once [the] concept [was] learnt' as there were 'too many ideas to combine otherwise'.

*[A compound is] a product which has properties different from those of either of the component substances and which is formed with an accompanying energy change is called a compound.*

This rather complex definition is difficult to apply, as was pointed out by one teacher who judged it as both 'wrong' and 'not helpful', and gave the example of the reaction between copper oxide and hydrogen: copper is a product with different properties, but is 'not a compound'. Of course, it is open

RS•C

to interpretation (*ie* definition) whether hydrogen and copper oxide are 'component substances' of copper.

In any case the student would already need to understand the ideas before the definition could be useful (it was 'good for redefining knowledge when pupils have fairly secure ideas' according to one teacher).

Another teacher thought that this definition was 'wrong' and 'not helpful',

'not sure but feel it would apply to alloys and to products where components are not elements'

Another teacher suggested that this definition was wrong as 'compounds are not necessarily different from the component substances', but unfortunately did not provide any examples to support this view.

## Atoms and molecules

In a similar way to our consideration of definitions of elements and compounds, we may consider how the concepts 'atom' and 'molecule' are defined in texts. Some examples of definitions of 'atom' are:

'The smallest part of an element which can exist as a stable entity.' [20]

'[Even though an atom is made up of smaller particles, as we will see shortly, it is still regarded as] 'the smallest particle of an element that still shows the chemical properties of the element.'...'[21]

'The smallest portion of an element that can take part in a chemical reaction.'[22]

'Atoms are the smallest particles that can be obtained by chemical means.'[23]

The following definitions of 'molecule' were found in common reference books:

'The smallest particle of matter which can exist in a free state' [24, 25]

'The smallest portion of a substance capable of existing independently and retaining the properties of the original substance.' [26]

'group of two or more atoms bonded together. A molecule of an element consists of one or more like atoms; a molecule of a compound consists of two or more different atoms bonded together.' [27]

[monatomic molecule] 'A molecule of an element, consisting of a single atom of an element. *eg* the molecules of the inert gases.' [28]

Again the comments of colleagues are interesting:

*[An atom is] the smallest part of an element which can exist as a stable entity.*

This definition is rather dubious, as it is not clear what is meant by 'stable'. One teacher pointed out that 'radioactive isotopes are not stable'. Most atoms certainly can be stable, under certain conditions (see Chapter 6). Under normal conditions (such as in a school laboratory) most discrete atoms would not be stable, and would readily interact to form molecules, ions etc. This view was not always supported by teachers considering the definitions.

One teacher judged this a 'correct' and 'helpful' definition, adding the comment: 'no problem'. Another teacher was 'not sure' if the definition was correct, asking 'how stable are protons and neutrons'. This is an interesting point, as a proton is stable in the sense of not undergoing radioactive decay: but, like most atoms, would not remain 'free' for long in most chemical environments[29]:

The word 'entity' in this definition was considered too difficult by one teacher.

*[An atom is] the smallest particle of an element that still shows the chemical properties of the element.*

RS•C

This is a very dubious definition. Firstly, it is difficult to know how chemical properties are defined for individual atoms. Under usual laboratory conditions the substance sodium reacts with water, the substance sulfur does not: it is difficult to know how one would judge the 'reactivity' with water of an atom of either element. (The term 'react' is not really applicable in this context – see Chapter 6.) Secondly, if one did try to evaluate the 'reactions' of the individual atoms, then atoms of substances would 'react' in conditions where the substance itself would not. An atom of carbon is going to be a 'reactive' species in chemical environments where bulk carbon is not. Again, teachers do not always take this viewpoint.

One teacher who thought that this definition was both 'correct' and 'helpful' described it as 'unproblematic'; and another thought it 'helps define 'stable entity' better to a younger pupil' and was 'OK for A level [*ie* post-16 level]'.

One teacher thought this definition was 'correct' but 'not helpful' as,

'This is a very theoretical type of definition. Testing it out would be impossible.'

A teacher who was unsure of whether the definition was correct posed the question 'how can an atom show properties of [the] element[?]', commenting that 'things like density etc are 'bulk' properties'. One teacher who judged this definition as 'wrong' because a 'Cl atom does not have [the] same properties as $Cl_2$', nevertheless thought it was 'helpful' to learners.

*[Atoms are] the smallest portion of an element that can take part in a chemical reaction.*

The biggest problem with this definition is that chemical reactions are macroscopic phenomena, and one should not confuse macroscopic and microscopic parts of explanations (see Chapter 6). In this case we find that such a confusion is very unhelpful. For example, if oxygen reacts, then it is certainly reasonable to say that the molecules of oxygen take part in the process. However, we could say that the atoms of oxygen take part in the reaction – and this could seem just as true. But it could also be said that the outer shell (valence) electrons take part in the reaction (which means they could be seen as atoms by this definition). This point was recognised by one teacher who argued that 'electrons take part in reactions', but other teachers found this definition 'correct' and 'helpful'.

*Atoms are the smallest particles that can be obtained by chemical means.*

This definition requires the learner to understand what is meant by the term 'chemical means' (see below) – as one teacher asked: 'is radioactivity chemical means?' – but it also seems dubious as most chemical process give a product which is molecular, or ionic, etc, and not a product which is atomic. Teachers asked about this definition disagreed about whether it was correct or not, and a number reported that they were unsure.

*[A molecule is] the smallest particle of matter which can exist in a free state*

For this to be useful the learner would need to understand what is meant by a free state. Even given this, some teachers would object to the definition. One teacher judged this as both 'wrong' and 'not helpful' because 'noble gases, metal vapour etc are monatomic'; another thought that the definition was correct, 'but causes problems for students with monatomic molecules'. As is discussed below, many teachers class monatomic molecules as atoms, but not as molecules.

The reference to 'the smallest particle of matter...' also causes problems, as one teacher suggested 'substance' might have been a more appropriate term here. Another teacher felt this was 'wrong' as it 'would confuse atoms with molecules'. A teacher who was unsure if the definition was correct suggested that 'if it's true it could be useful'!

*[A molecule is] the smallest portion of a substance capable of existing independently and retaining the properties of the original substance.*

This is very similar to some of the definitions of atom given above. The first section of this statement seems less dubious in this context as molecules do commonly exist independently (where atoms do not).[30] The second part of the definition is more problematic. Molecules of a substance can be

RS•C

considered to show some of the properties of a substance (sometimes colour, smell), but, again, can not really be considered to have bulk properties such as hardness, density or conductivity. As one teacher (who judged the definition to be 'wrong') explained;

'a single molecule can't be solid, liquid or gas as it is the interaction with others that give the state of the matter'.

One teacher judged this definition as 'correct' and 'helpful' and 'unproblematic'. However, other teachers who also considered this definition as 'correct' judged it as 'not helpful' as it was 'too complicated & subtle' and the language was 'too difficult' for learners.

*[A molecule is a] group of two or more atoms bonded together. A molecule of an element consists of one or more like atoms; a molecule of a compound consists of two or more different atoms bonded together.*

This definition is not self consistent, as the second sentence, allowing the possibility of monatomic molecules, contradicts the first. Yet some teachers considered it both 'correct' and 'helpful': describing it as a 'good definition at KS4 [*ie* for 14–16 year old students]'; 'useful at end [of teaching the topic]', and noting that it 'distinguishes between elements and compounds'. One teacher who thought it was 'wrong', nevertheless thought it was 'helpful' and the 'definition most people work with'.

*[A monatomic molecule is] a molecule of an element, consisting of a single atom of an element. Eg the molecules of the inert gases.*

In my own undergraduate study I was quite familiar with the notion of monatomic molecules, as opposed to diatomic or polyatomic molecules. One teacher who thought that this definition was 'correct' thought that it was 'helpful' as 'the definition gives an example'. Yet, I am aware that many chemistry teachers do not feel that a single atom should be described as a molecule, even when the atom is stable, and is the smallest part of the element which may be considered to share some of its properties (*ie* the noble gases).[31] One teacher, classing this definition as both 'wrong' and 'not helpful' explained that 'I don't think Ar is a molecule!' Another was more insistent that a 'single atom is not [a] molecule'. One teacher who was unsure about the accuracy of the definition explained,

'I think 'monatomic molecule' is a contradiction in terms.'

Clearly if teachers themselves consider that a molecule is always a group of atoms, then they will teach that monatomic molecules [*sic*] are not molecules. One colleague who piloted the materials in the companion volume on **Elements, compounds and mixtures** reported that the students 'have been taught that substances like Ne, Ar, etc have particles that are atoms (NOT molecules)'.

## Physical and chemical change

The distinction between chemical and physical changes is often presented as important and unproblematic at secondary level (see Chapter 6). If this is so then science teachers should be able to agree on the classification of processes as chemical or physical and also on the reasons for their decisions (based upon the definitions they use). As part of the present project teachers were asked to undertake such an exercise (*ie* classifying changes as physical or chemical and explaining why).[32] As would be expected, many processes are not problematic in such a context. Freezing liquid nitrogen is agreed to be a physical change, and burning magnesium in oxygen is accepted to be a chemical change. However, such a common-place example as dissolving salt ('some sodium chloride is added to a beaker of water, and left to dissolve') did not lead to a consensus. This was commonly felt to be a physical process as;

- it 'can be reversed by physical means' and 'reversed easily';
- there were 'no structural changes to $H_2O$';
- there was 'no new substance made', 'no new compound', 'no change in chemical composition';

RS•C

- 'NaCl remains in ionic form only separated by $H_2O$ molecules';
- one could 'extract NaCl out again unchanged'; and
- there were 'no apparent heat changes'.

Despite these views some teachers thought that this change could not be categorised:

'Although process is reversible, the sodium and chloride ions are separated when they are hydrated.'

'This is usually described as a physical change as it is easily reversed. However, according to some other ways of describing (*eg* in terms of bonding and types of substance produced) it could be put in the other category.'

One teacher wanted to count this process as both physical and chemical:

'BOTH! Solid NaCl easily recovered, but new particles formed (*ie* hydrated ions) which did not exist in original'

And some teachers feel this is a chemical change with 'bonds broken':

'I would argue (but not to my classes) that this is a chemical change – ionic bonds broken, ions hydrated.'

The definitions teachers were using provided criteria for making a judgement – easily reversible, new substances formed, bonds broken, energy changes – but these criteria were not adequate for agreeing on a definite classification (see Chapter 6). This is not an isolated example. Another process commonly observed in school laboratories (the heating of copper sulfate crystals to 'drive off' water of crystallisation) also divided teachers on whether it was a physical change, a chemical change or could not be categorised.

## Implications for teaching chemical concepts

This chapter has tried to show why teaching chemical concepts is not a clear cut and straightforward matter. People have an aptitude for quickly learning new concepts such as 'tree' and 'animal', yet the process that helps us learn these 'natural categories' may not be very helpful when we need to learn scientific concepts that are usually delimited by technical definitions.[33]

When we do work with formal definitions (which we expect our students to understand, learn and apply) we often find that they are not that helpful for students. They may be incomplete and only have limited application. They may be wordy and require prerequisite understanding of other equally difficult concepts. Some definitions we find in the books students might refer to have both failings.

If full definitions are too involved for the students, and if partial definitions are only a stop-gap strategy, then a middle way is needed. Perhaps the best approach is to keep things simple, but to emphasise the provisional nature of the definitions used.

'The idea of oxidation is very important to scientists. When oxygen is added we say a substance has been oxidised. This is not the only way of deciding when something is oxidised, but this is useful for us now. At the moment you only need to know about this way of deciding if something is oxidised...'[34]

In this chapter I have also tried to show that even when we take such an approach there is a basic problem with the definitions which we teach and assess in our classes. Even when experienced teachers are asked to consider basic chemical concepts we find that these experts cannot agree on which definitions are accurate (let alone helpful to students). Presumably the teachers helping in this exercise had little trouble knowing when they were dealing with elements or molecules – but found definitions of these ideas problematic.

When teachers were asked to categorise familiar processes according to a distinction often taught at lower secondary level (*ie* chemical and physical changes) they used the accepted criteria from standard school definitions but came to different conclusions.

RS•C

I feel these exercises, generously undertaken by colleagues who sometimes had thirty years teaching experience, demonstrate a serious problem about teaching chemical (or other technical) concepts.

Definitions are very important in science, and have a role in learning: but we develop our scientific concepts by a more convoluted process. We only fully appreciate our definitions in the context of developing understanding of the very concepts they are supposed to help us learn.[35] Most definitions are of limited application, or obscurely worded, until we already understand them in their context through using the concept and its definition widely.

When teaching we must use definitions carefully. It may well be appropriate to introduce them at an early stage in a topic, to allow students to become familiar with them, but teaching a definition does not in itself teach the concept. The best that can be expected is rote-learning until the student has enough context to make the definition sensible.

If concepts cannot usually be effectively taught through definitions, then it becomes important to have a useful alternative approach to thinking about how concepts are developed. In the next chapter it will be suggested that scientific concepts cannot be meaningfully learnt in isolation, but need to be learnt in terms of their relationships with each other.

## Notes and references for Chapter 2

**1.** Important types of schema are 'frames' (by which we model the structure of our physical environments such as rooms), 'scripts' (by which we make sense of routine activities such as eating a meal, shopping or teaching a class) and 'concepts'. See R. T. Kellog, *Cognitive Psychology*, London: SAGE Publications, 1997.

**2.** Clearly the child's brain is recognising trees according to some physical process. This could mean the brain is following rules that are too complex or subtle for us to have discovered – but this seems unlikely. Research into 'neural nets' show that fairly limited 'artificial brains' (using simple electronic components) can be 'trained' to recognise patterns – such as sonar signals reflecting from submarines – without having been programmed with any specific algorithm. This ability of nets of neurons (or transistors) only requires feedback on the success of previous attempts to make identifications. As the human brain is much more complex, and has structures already in place through evolution, this may explain how much successful learning of concepts occurs with very sparse feedback.

**3.** An extreme example is the learning of human languages. The paucity of the input available to a young child learning its mother-tongue convinced Noam Chomsky that the child's brain contains some structure which has evolved to readily acquire any language which fits a certain basic pattern (and therefore that all natural human languages have an underlying similarity despite obvious differences). This 'language acquisition device' is part of the cognitive apparatus that develops in all normal humans. The 'device' may not be a located at one specific site in the brain, but is still actually part of the physical structure of the brain. See S. Mithen, *The Prehistory of the Mind: a search for the origins of art, religion and science*, London: Phoenix, 1998.

**4.** This distinction may sound familiar to readers who have read about the work of Lev Vygotsky, who distinguished 'spontaneous' and 'scientific' (*ie* learned-through-teaching) concepts. See L. Vygotsky, *Thought and Language*, London: MIT Press, 1986.

**5.** D. M. Watts & J. Gilbert, Enigmas in school science: students' conceptions for scientifically associated words, *Research in Science and Technological Education*, 1983, **1** (2), 161–171.

**6.** Many of these terms were borrowed from everyday use, and then had a tighter meaning imposed upon them by physicists. This practice still continues, and while the use of terms such as 'charm' 'truth' and 'beauty' are not likely to lead to serious confusion between their scientific and everyday meanings, the idea of 'spin' (as in electron spin) is certainly a source of learning problems.

RS•C


7. C. Sutton, *Words, Science and Learning*, Buckingham: Open University Press, 1992.

8. K. S. Taber, Can Kelly's triads be used to elicit aspects of chemistry students' conceptual frameworks?, 1994 – available via Education-line, at **http://www.leeds.ac.uk/educol/** (accessed October 2001).

9. The reason for using three diagrams, and asking students to select an odd-one-out is to allow students to make discriminations when they are not sure of the appropriate labels for their ideas.

10. A. H. Johnstone & D. Selepeng, A language problem revisited, *Chemistry Education: Research and Practice in Europe*, 2001, 3 (1), 19–29, available at **http://www.uoi.gr/conf_sem/cerapie/** (accessed October 2001).

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

12. K. S. Taber, An analogy for discussing progression in learning chemistry, *School Science Review*, 1995, **76** (276), 91–95.

13. For example, in the National Curriculum for England, see *Science: The National Curriculum for England*, London: Department for Education and Employment / Qualifications and Curriculum Authority, 1999.

14. J. G. A. Raffan *et al*, *Chemistry for Modern Courses*, Sevenoaks: Hodder & Stoughton, 1975, 33.

15. Oxford Science Programme: *Materials and Models* Oxford: Oxford University Press, 1993.

16. Oxford Science Programme: *Materials and Models* Oxford: Oxford University Press, 1993.

17. P. Lafferty & J. Rowe, *Dictionary of Science*, London: Brockhampton Press, 1997.

18. J. G. A. Raffan *et al*, *Chemistry for Modern Courses*, Sevenoaks: Hodder & Stoughton, 1975, 27.

19. The science teachers were attending presentations about the RSC **Challenging Misconceptions in the Classroom** project which led to this publication, at meetings arranged by the ASE (Association for Science Education). The teachers completed a version of the classroom activity **Definitions** included in this publication, but with the inclusion of an additional item on 'monatomic molecule'.

20. D. W. A. Sharp, *The Penguin Dictionary of Chemistry*, Harmondsworth: Penguin, 1983.

21. K. Gadd & S. Gurr, *University of Bath Science 16–19: Chemistry*, Walton-on-Thames, Surrey: Thomas Nelson & Sons Ltd, 1994, 16.

22. E. B. Uvarov, D. R. Chapman & A. Isaacs, *The Penguin Dictionary of Science* (5th Edition), Harmondsworth: Penguin, 1979.

23. J. Morris, *GCSE Chemistry*, London: Collins Educational, 1991, 264.

24. D. W. A. Sharp, *The Penguin Dictionary of Chemistry*, Harmondsworth: Penguin, 1983.

25. The context for this definition was 'The smallest particle of matter which can exist in a free state (see atom). In the case of ionic substances such as sodium chloride, the molecule is considered as NaCl, which exists as an ion-pair in the gas phase, although the solid consists of an ordered arrangement of $Na^+$ and $Cl^-$ ions.' See Chapter 7 for a consideration of ionic 'molecules'.

26. E. B. Uvarov, D. R. Chapman & A. Isaacs, *The Penguin Dictionary of Science* (5th Edition), Harmondsworth: Penguin, 1979.

27. P. Lafferty & J. Rowe, *Dictionary of Science*, London: Brockhampton Press, 1997.

28. E. B. Uvarov, D. R. Chapman & A. Isaacs, *The Penguin Dictionary of Science* (5th Edition), Harmondsworth: Penguin, 1979.

RS•C

29. The same is not true for free neutrons which have a surprising short half-life of a thousand seconds, *ie* less than twenty minutes: R. D. Harrison, *Nuffield Advanced Science Book of Data (Revised Edition)*, London: Longman: 1985.

30. Of course the stability of any species depends upon the conditions. Most molecular materials that are not gaseous will become so on heating, and so fit this definition. Continued heating (without the opportunity for reaction) will lead to gaseous atoms, but then if heating was continued the atoms would be ionised, and eventually the nuclei will break up, and even the protons and neutrons would not be stable at a high enough temperature. Under the conditions we normally consider, atoms do not usually have 'independent' existence.

31. This is not a new issue. A letter to the School Science Review in 1961 criticised an article defining the molecule as 'a group of atoms bonded to one another', and championed instead 'the smallest separate particle of a gas which moves about as a whole'. The letter's author pointed out that this definition of molecule would include 'species consisting of 1 atom only' – J. W. Davis, Molecules & Ions, *School Science Review*, 1961, **43** (149), 195–196.

32. Some responses were obtained from teachers attending presentations about the RSC **Challenging Misconceptions in the Classroom** project which led to this publication at ASE (Association for Science Education) meetings, and others by post from colleagues volunteering to trial materials.

33. W-M. Roth, Artificial neural networks and modelling, knowing and learning in science, *Journal of Research in Science Teaching*, 2000, **37** (1), 63–80.

34. More research is needed to find out how students will respond to such approaches, but based on what is known at present this would seem to be 'best advice'.

35. K. S. Taber, Time to be definitive?, *Education in Chemistry*, 1995, **32** (2), 56.

This page has been intentionally left blank.