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3. The structure of chemical knowledge

This chapter considers the way knowledge is structured in chemistry, both formally and by individual learners. The chapter also includes a consideration of 'concept mapping', a simple and useful technique which can be used for planning lessons, for diagnosing aspects of how learners structure their knowledge, and as a useful study and revision tool.

Concepts take their meanings within knowledge structures

The previous chapter (on concepts in chemistry) discussed what is meant by a concept, and how such concepts may be formed so that learning can take place. One key aspect of looking at the meaning of a concept is an awareness that it is difficult to consider particular concepts in isolation. When we define concepts we usually do so in terms of other previously learnt concepts (see Chapter 2). It is clear, then, that the meaning of a single concept depends upon how we understand it in relation to other ideas. In other words, in order to understand what we mean by a chemical concept we need to see how it fits into a wider structure of ideas. We need to help students 'make the connections'[1] to develop their own conceptual frameworks. This chapter considers this idea of knowledge structures in chemistry.

Formal and personal ways of structuring chemical knowledge

One type of knowledge structure is that of chemistry itself. I will call this formal organisation of chemical knowledge the conceptual structure of the subject. This is the way chemical knowledge itself is organised 'officially'. We can find out about the conceptual structure of chemistry from journals and books. This type of structure is very important to teachers, both because in a sense it is the subject matter that we teach, but also because it is an important tool for planning effective lessons.

The second type of knowledge structure is that in the minds of learners: their own personal ways of relating and understanding chemical ideas. The way learners represent knowledge is very important. For one thing the students' existing knowledge structures are an important determinant of what and how they learn new material (see Chapter 4). Also, if we accept that concepts only take their full meaning in relation to each other, then we need to know about the way a learner makes relationships between different ideas before we can judge if they understand them as intended. The term cognitive structure is used to describe the way a person's knowledge is organised.

It is not possible to directly observe cognitive structure, so it must be inferred from indirect evidence (such as answers to the teacher's questions and the responses made in tests and other probes).

The conceptual structure of chemistry

A curriculum subject such as chemistry is not a set of isolated facts or principles. Chemical knowledge is structured. Not every chemistry teacher or chemist would agree on precisely what that structure is, and, anyway, it is a fluid structure. The structure of the subject now is different from 50, 100 or 150 years ago, as the subject has developed.[2]

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For example, the 'traditional' division of chemistry into inorganic, physical and organic branches (see Figure 3.1) has become less significant in recent years,[3,4] with much important work done across divisions (so we have physical organic chemistry as a field in its own right, and developments in areas such as organic conductors, and organometallic chemistry) and even across the boundaries of the discipline (in materials science, molecular science, biochemistry, geochemistry, *etc* – and a rather arbitrary distinction between some aspects of physical chemistry and the field of 'chemical physics').[5]

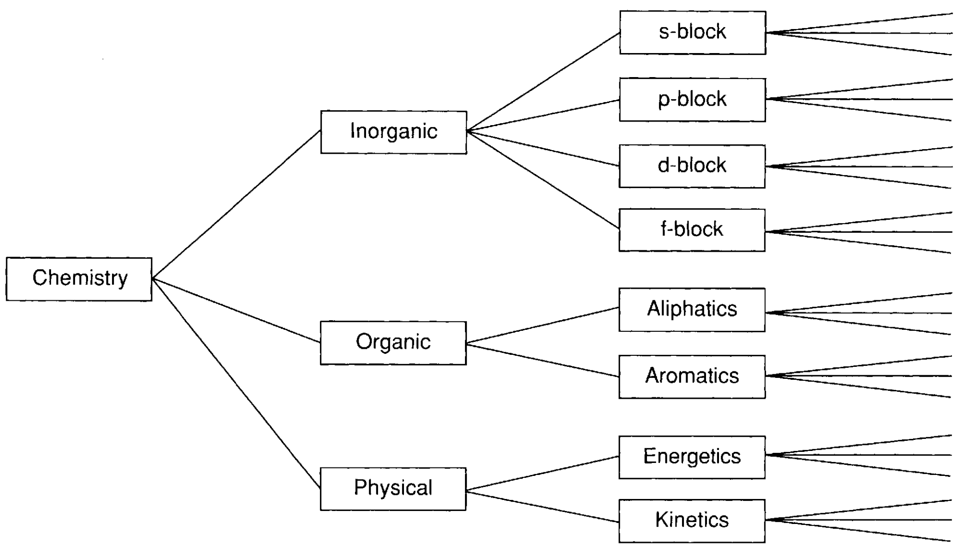

Figure 3.1 One way of structuring chemistry

Yet to some extent this break-down of the 'traditional' subject structure is merely a reflection of the advances in theory and the available techniques which have seen – for example – quantum-mechanical calculations and spectroscopic and related techniques become more important. Indeed, the development of the subject can largely be related to the increasing role of electronic structure as an organising theme for the subject.[6]

The structure of chemistry has shifted, but it no doubt exists. This is unavoidable, due to the nature of knowledge itself. As was considered in the previous chapter, all of our concepts take their meaning from the way they relate to one another (see Chapter 2).

To some extent we can see chemical concepts as hierarchical, starting with the most basic definitions and distinctions (some of which are considered in Chapter 6). So the notion of substance is fundamental – and allows us to define what we mean by chemical reactions (a theme discussed in more detail in Chapter 9) - and pure substances are divided into elements and compounds. The idea that matter is quantised (the molecular model) rather than continuous is another key tenet of the subject. Once we see matter in this particular way, a key concern becomes how the particles are arranged (*ie* chemical structure – see Chapter 7), and how they are held together (*ie* bonding – see Chapter 8) and how rearrangements may occur (*ie* reactions – see Chapter 9).

One might see other concepts as being at less significant levels of the hierarchy – so once the quantum model of matter is established, it is possible to look in more detail at atomic, and indeed nuclear, structure. Once we have a concept of element we can consider what we mean by metals and non-metal, and by finer distinctions such as transition metals or halogens.

However, we soon find that a hierarchical structure does not do justice to the sophistication of our subject! For example, our periodic classification ties the concept of element to ideas about atomic structure, and to the notion of substance. As well as dividing substances according to positions in the

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Periodic Table we have other classifications such as acids and bases, and oxidising and reducing agents (which may be elements or compounds).

It soon becomes clear that there is no simple hierarchical relation between our concepts, but rather that they are organised into a kind of web or net: a structure with many nodes (concepts) connected by a complex network of relationships. Needless to say, this very complexity makes teaching chemistry a complicated, demanding, but rewarding business.

Representing knowledge structures: the concept map

Textbooks, and lessons, inevitably present material in a linear fashion. A book has to place some material ahead of others, and a teacher has to introduce some ideas before others. The nature of our world – of space (on a page) and time (in a lesson) – does not provide any alternative!

Yet the nature of chemical knowledge does not readily fit into such a spatial or temporal sequence. A graphical approach – something more like a diagram – might be a more appropriate way of representing our knowledge about chemistry (and many other subjects). For example, synthetic reaction schemes are often presented in a graphical form.[7] A concept map is a useful graphical representation, that can be used for any information that does not readily fit a linear pattern.

There is a large literature on concept mapping[8,9,10,11] and related techniques, and there are many variations on how such 'maps' may be produced. Anyone who finds the ideas presented in this chapter particularly helpful may wish to read up further, but in my own practice I have found a simplistic approach sufficient.

Take a look at the concept map in Figure 3.2.

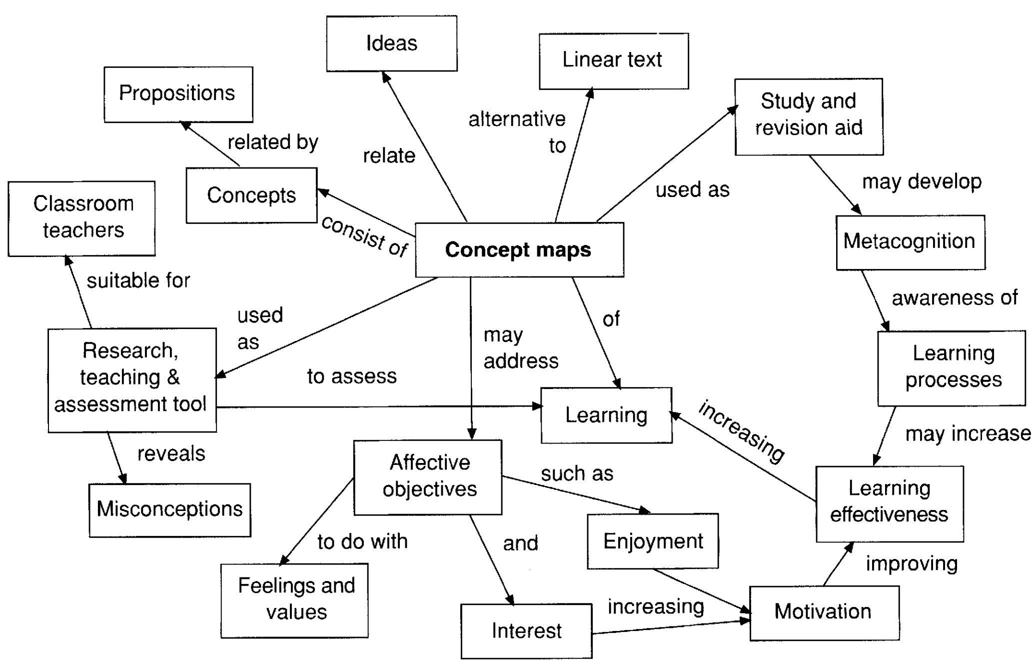

Figure 3.2 A concept map for the concept 'concept map'[12]

This is a concept map for the concept of 'concept map'. 'Read' the map. Note that there is no one and only correct 'order' for reading the information.

The map has two types of components:

- nodes – representing 'concepts'; and
- connections – representing propositions that relate the nodes.[13]

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Such a representation is a type of model – a graphical model of some aspect of human knowledge. As a model it is under the author's control (see Chapter 6). When preparing such a map you can (and indeed need to) make decisions about;

- what the central concept will be;
- the amount of information to be included;
- the types of concept labels to include; and
- the amount of detail required for connections; *etc.*

The central concept: in this case the concept is 'concept map', but it could have been 'chemistry' (and Figure 3.1 could be seen as a type of concept map), 'metals', 'oxidation', 'rates of reaction', *etc.* Do not be precious about what is meant by the word 'concept' (see Chapter 2) - if you can label an idea it probably counts as a concept.[14] It is useful to bear in mind, however, that such specific concepts are embedded in larger complex networks of ideas. In drawing a concept map we select the central idea and try to extract the most salient connections.

The amount of information: just like the party game of connecting two movie stars or rock musicians through a sequence of fellow artists they have worked with, or films/albums they have worked on, it is possible in principle to connect any concept with any other – by increasing the number of 'degrees of separation' allowed. Concept maps can become too complicated, and too dense with information to be useful, so it is important to be selective in what is included. (If a map is getting too dense it is always possible to replace it with several maps, which are inter-linked – just like city maps which have central sections reproduced in more detail at a different scale.)

Concept labels: it is best to keep the node labels concise, and familiar. Although concept maps avoid the need to arrange knowledge in hierarchies (like identification keys) some concepts have greater generality than others. For example, the concept 'base' is more general than the concept 'alkali'. Where a map includes concepts of different generality, the more general concepts are usually located more centrally, and the more specific concepts more peripherally. Some concepts are so specific that they are best seen as examples (*eg* 'sodium hydroxide'), and usually fit best near the edges of a concept map. Sometimes examples may be represented differently (say, not having a box around them) to show they are considered less fundamental to the structure being described.

Connections: a connection on a concept map is usually of the form of a proposition: that is a sentence which shows how the two concepts are connected. A line connecting 'alkali' and 'base' might represent 'an alkali is a type of base', or 'an alkali is a soluble base'. (Note that both of these propositions show that 'alkali' is a type of 'base' - but more specific information is given in the second example.) It is possible for the propositions to be written in full on the map, or abbreviated into note form, or just represented by a number or letter key – in which case the propositions may be listed separately. The propositions in Figure 3.2 are indicated by arrows, but often they will just be lines.

Concept maps are tools to help us represent (and explore and develop – see below) our knowledge, and should be used flexibly. It is not helpful to impose too many rules about how we should draw them.

Circular definitions or spiral curriculum?

In the previous chapter we saw that learning scientific concepts can be very problematic. To summarise some of the points made there:

- chemical/scientific concepts are usually defined by rules;
- the rules are often subtle and difficult to explain; and
- defining the concept is usually only possible in terms of other concepts which also need to be defined.

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This can potentially lead us to a problem where we can only understand concepts in terms of the other concepts to be learnt – a 'vicious circle' (see Figure 3.3).

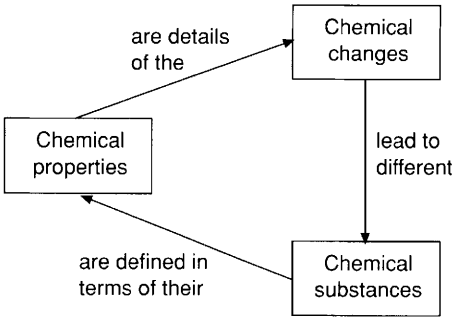

Figure 3.3 A concept 'circle'

So, for example we might define a chemical change as one which leads to new substances, but we would need to know how to distinguish substances to know if the product was different (or just the same substance in a different form). We can characterise a chemical substance in terms of its chemical properties, that is the details which chemical changes it undergoes. But this, of course, needs us to understand what a chemical change is... This 'concept circle' would seem to have no starting point.

There are many other examples that could be given, as the previous chapter suggests. Clearly, many of our students do acquire acceptable versions of such concepts, so in practice students can enter the 'concept circle'.

A key point to appreciate here is that learning chemical concepts is not an 'all-or-nothing' experience. We expect our lower secondary students to acquire a working concept of, say, chemical compound, but we appreciate that this understanding will at first be tentative, and even 'fragile'. As the student moves through the secondary school, and then perhaps through college and maybe even university study of the subject, we expect their appreciation of the concept to become, deeper and more robust.

As the student better understands one concept, he or she can begin to have a better appreciation for all the other concepts that are closely linked to it.

This is the rationale for having a 'spiral curriculum', where topics are introduced, and later revisited in increasing depth. This approach has two powerful advantages. Firstly we know that the actual process of 'fixing' concepts in the brain does not take place instantly. The permanent changes in brain structure which lead to long-term learning take place in the days, weeks and perhaps even months after the 'learning experience' in class. Revisiting a topic frequently may influence this process of 'laying down' permanent memory traces.

Conversely, ideas that are not used at all for months may not leave very strong traces in memory. Many good teachers use a 'drip-feed' approach: gently and briefly reiterating key ideas and concepts when a teaching opportunity arises. This reinforces learning both by emphasising the significance of the concept, and by providing links to other curriculum topics.

The second advantage of a spiral curriculum is that between successive stages of exploring a topic (such as acids) other topics will have been visited (perhaps combustion, metals, water) and new links can be developed which were not possible before. For example, if oxidation is studied first in the context of combustion, and subsequently the student studies displacement reactions between metals and metal salts, this provides a new context for revisiting and expanding the oxidation concept that was not available before.

Formal curriculum structures may include deliberate attempts to build upon the idea of a spiral curriculum, but will only be successful if there is genuine progression in the depth and breadth of the treatment each time a topic is studied. [15]

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Initiating a learning spiral

Seeing learning in terms of concept-spirals overcomes the obvious problem of concept-circles (where teaching any concept requires understanding of another, which in turn depends upon...). However, it is clear that it does not avoid the problem of how to get such a learning spiral going.

This means that the teacher needs a starting point that learners can relate to: something that is already familiar, and can be used as the substrate for new learning. (When such a connection is not made, useful learning is usually blocked – see the next chapter). The new material must be 'anchored' to this substrate by a suitable 'hook' – something that relates what the learner already knows with the chemical ideas to be acquired.

Sometimes there are obvious targets in the learners' existing experiences. To take an example: all students are familiar with fires (bonfires, burning candles, seeing house fires on the TV news *etc*), and so this makes a suitable starting point for introducing the chemical concept of combustion. The student can learn this label, and associate it with their everyday experience of burning. This can then later be a suitable hook for teaching about the concepts of 'chemical change', 'oxidation', and later 'exothermic reactions'.

Sometimes such obvious targets are not available. Often the obvious place to start is not within everyday experience, but in terms of formally taught prior learning (an approach which can go wrong when the prerequisite learning is not what the teacher assumes – see Chapter 4). On other occasions, when the new ideas are especially abstract or obscure to learners, it may be necessary to form links with existing knowledge by developing analogies from the familiar to the novel idea being taught. (The effective use of analogies needs careful planning, as is discussed in Chapters 7 and 10.)

Often the teacher needs to undertake a formal 'content analysis' of a topic.[16]

Concept maps as teaching tools: content analysis

Whenever a teacher has to teach a new topic it is sensible to undertake a form of content analysis, which:

- determines the precise ideas that need to be covered;
- how they are inter-related; and
- what other concepts will be needed to teach the new ideas.

The material to be covered is often laid down in curriculum documents or in a school or college's schemes of work. The teacher will need to decide in which order to introduce ideas, which is why a logical analysis of how the concepts are related is important.

However, it is just as important to consider the pre-requisite knowledge that is being assumed in teaching the topic. This is because:

(a) sometimes students do not hold the assumed prior knowledge (or hold alternative distorted versions of it), and so it is important for the teacher to check that students have an acceptable understanding of these ideas before setting out on the new exposition (many of the resources in this publication are probes suitable for diagnosing students' ideas).

(b) the links with prior knowledge need to be made explicit – sometimes these ideas are so familiar and obvious to the teacher that they are not emphasised enough for the students to spot them. This can lead to the new learning lacking 'anchors' in existing knowledge, and (to follow the nautical metaphor) floating away to become isolated icebergs of knowledge, or breaking up to give conceptual flotsam with no coherence or utility to the student, and conceptual jetsam washing up to form inappropriate links with other islands of knowledge. (These different types of learning blocks are discussed in the next chapter.)

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(c) the new topic provides opportunities to reinforce many key ideas from previous teaching by the drip-feed approach (see above).

There are many ways to undertake such an analysis of content. One way is a kind of programmed learning approach, where the entire topic is reduced to a series of logical statements, and each of these propositions is sequenced so that each statement introducing a new idea is grounded in the earlier statements. If done effectively such an approach can be very useful, and it may well appeal to some teachers with particular 'thinking styles'. Some of us like to think through linear, logical steps – and may find such an approach useful and reassuring. (Do you like writing computer programmes, working on legislative committees, or undertake analytical philosophy for fun in your spare time? Some people do!)

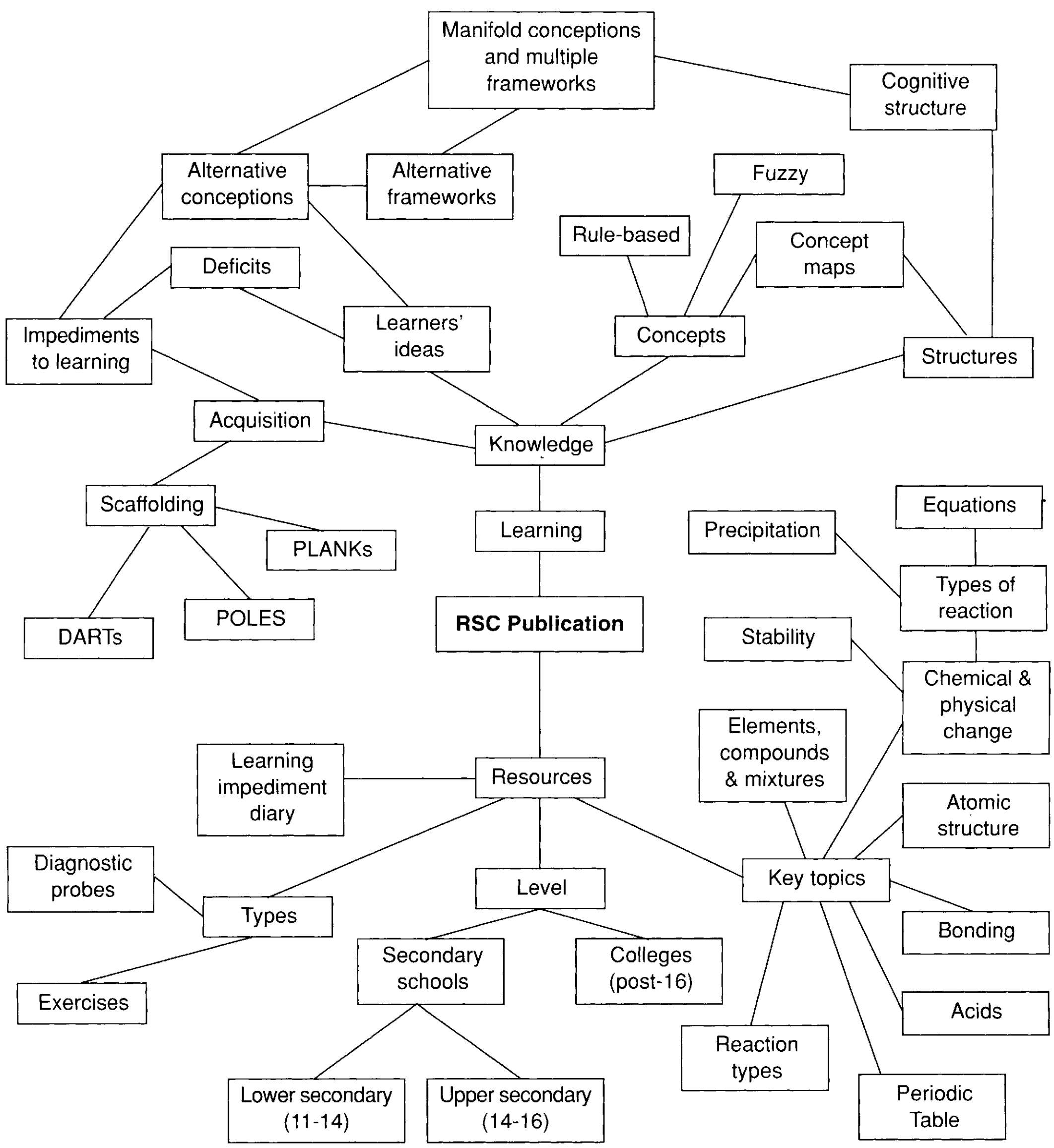

Figure 3.4 A way of representing the contents of this project

However, if such an approach does not appeal, you may find concept mapping as an easier way of working. Some teachers will prefer a visual way of representing information such as a concept map, rather than an ordered list of statements. For example, this publication includes a contents list, which is one way of finding out what it contains. However, the contents could also be shown in a diagrammatic form, like a type of concept map (see Figure 3.4).

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Some may prefer using a concept map, because they find constructing such a diagram much easier than just writing out sequences of sentences. Concept maps are a form of representation which lends itself to revision as understanding of a topic develops – something that has been found useful for teachers as well as students.[17] The concept map can be compiled in the order in which ideas hit you: start with your central theme, and just add things in until you feel you have covered the topic.

For example, consider the topic of acids as it might be presented at lower secondary level. The following concept map (see Figure 3.5, which is a reduced version of one of the classroom resource sheets included in this publication) could represent the teacher's plan for covering the topic. This map can then be a tool for planning individual lessons. (See, also, the concept map for hydrogen bonding in Chapter 5, Figure 5.3.)

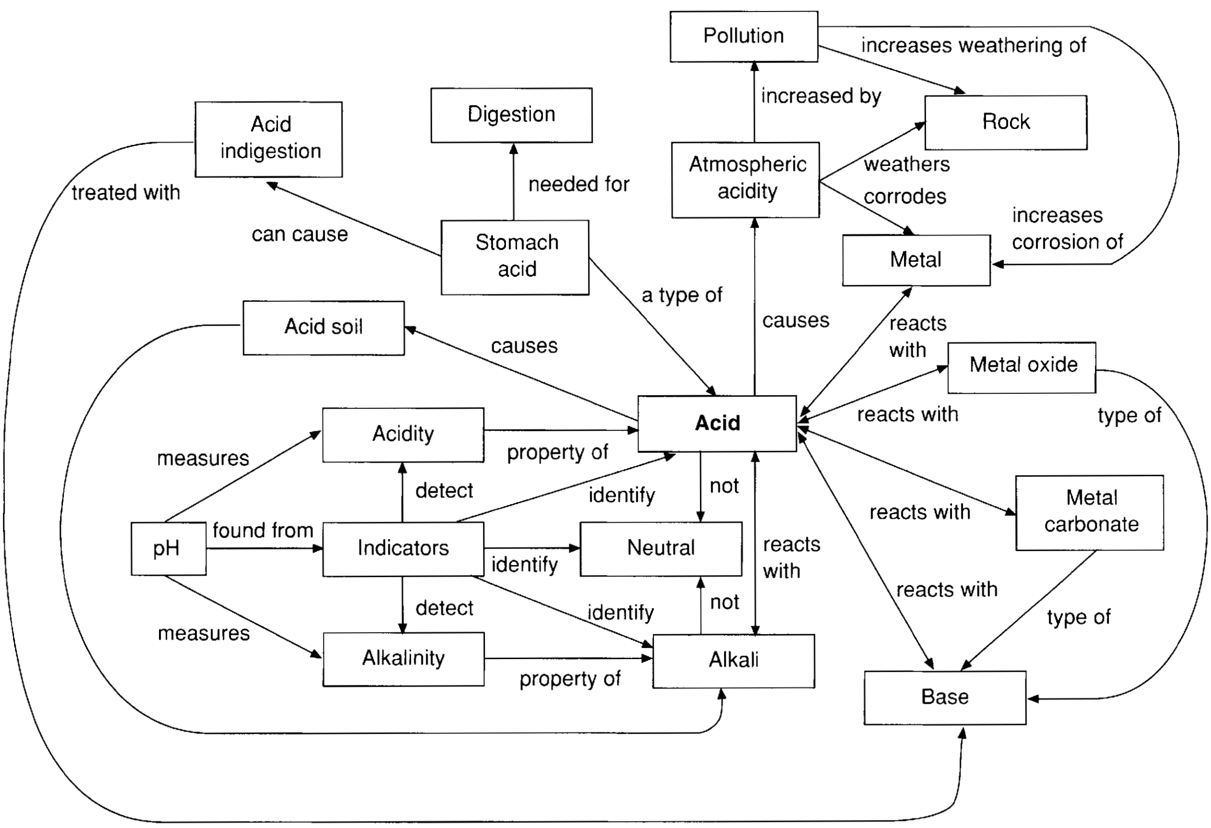

Figure 3.5 A concept map for 'acids'

Dimensions of cognitive structure

'Cognitive structure' is a way of labelling the ideas available to a learner. Using such a technical term might give the impression that this something that is well understood. In practice we do not really have a detailed understanding of how we store our knowledge.

One definition of cognitive structure is:

'the facts, concepts, propositions, theories, and raw perceptual data that the learner has available to her at any point in time, and the manner in which it is arranged'. [18,19,20,21]

A key point about this definition is that it includes the way knowledge is organised – as well as what knowledge is present. (If you have agreed with the earlier ideas in this and the previous chapter you will realise that this has to be so: the way concepts are related is a key part of what those concepts mean to us.) If we are interested in how well a student understands a subject like chemistry it is at least as important to know how they understand the concepts to be related as to know which concepts they have 'acquired'.

As has been pointed out above, concepts like oxidation or acid can be understood at increasing levels of sophistication as a learner passes through the school and beyond. A student could learn a definition of 'alkali' by rote, without necessarily having the understanding to apply the idea in appropriate contexts. Clearly questions such as 'has the student acquired the concept of acid' or 'does the student understand oxidation' are not very helpful unless prefixed by 'to what extent'.

Given that we are a long way from being able to 'read minds' directly and do not understand enough about how concepts are 'stored' within brains, we must rely on indirect evidence. Luckily, every time a student answers, or asks, a question, or writes about their chemistry, they provide such evidence. The activities in this resource are largely designed to be targeted at looking for evidence in key areas where we know students often do not understand topics the way we want. There has been a great deal of research to find out how students do make sense of scientific ideas (see Chapter 1) and that vast body of work provides a great deal of data about learners' ideas.

At one level this tells us a lot about which 'alternative conceptions' student commonly demonstrate. Unfortunately, however, different research, carried out by various researchers using disparate techniques, leads to different inferences about the way students store their ideas. The sensible (indeed common-sense) approach to interpreting this research is to take a view that learners' ideas vary along a number of dimensions, such as:

- tentatively held – deeply believed;
- alternative ('wrong') – conventional ('accurate');
- idiosyncratic – common;
- isolated conceptions – integrated frameworks; and
- unitary (consistent) – manifold (multiple frameworks).

We all have some ideas which are held quite provisionally (usually when the topic is not important to us, and/or the source is not considered reliable, and/or we are aware we only picked-up on part of the information: perhaps we hear the end of a radio news item about an election in some country we know little about). Other beliefs we treat as absolute matters of creed (*eg* England is joined to Scotland, and all people are entitled to be treated fairly in law). In the same way, students may hold some ideas quite tentatively ('I think manganese is a metal, but I'm not sure) and others very strongly ('I know reactions occur so that atoms can get full shells of electrons'). The strength of a conviction does not always relate to the accuracy of the idea!

Similarly, we each have topics where we know a few isolated facts, which are not strongly linked to anything else (how much do you know about romantic poets, or prohibition in the USA, or icons of the Russian church, or stone age hand tools, or Jung's notion of archetypes?) As science teachers, our knowledge of chemistry tends to be well integrated, coherent, and logically arranged, but many of our students have much more piecemeal knowledge (and they may find our knowledge of their favourite pop group/football team/television soap to be rather limited and fractured).

The final dimension above is not so obvious, but may be very important. People often hold alternative mental representations of the 'same' concept in their minds. It has long been known that some students seem to compartmentalise their formal school learning about some science topics separately from their everyday knowledge of the same topics (see Chapter 1). So a learner may show a good understanding of pH in a test, but refuse to drink something that is labelled acid in a normal social context, or may well know the difference between melting and dissolving in the laboratory, but talk of the sugar melting in the tea at home.

This phenomena of having separate scientific and 'life-word' versions of concepts has been seen as being related to the extent to which students integrate their ideas. Indeed it has been suggested that

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students' learning tends to be fragmentary and so their ideas exist as set of isolated 'minitheories'.[22] This, however, is unfair. Consider the following example of a (redrawn) student's concept map for the topic 'energy' (see Figure 3.6):

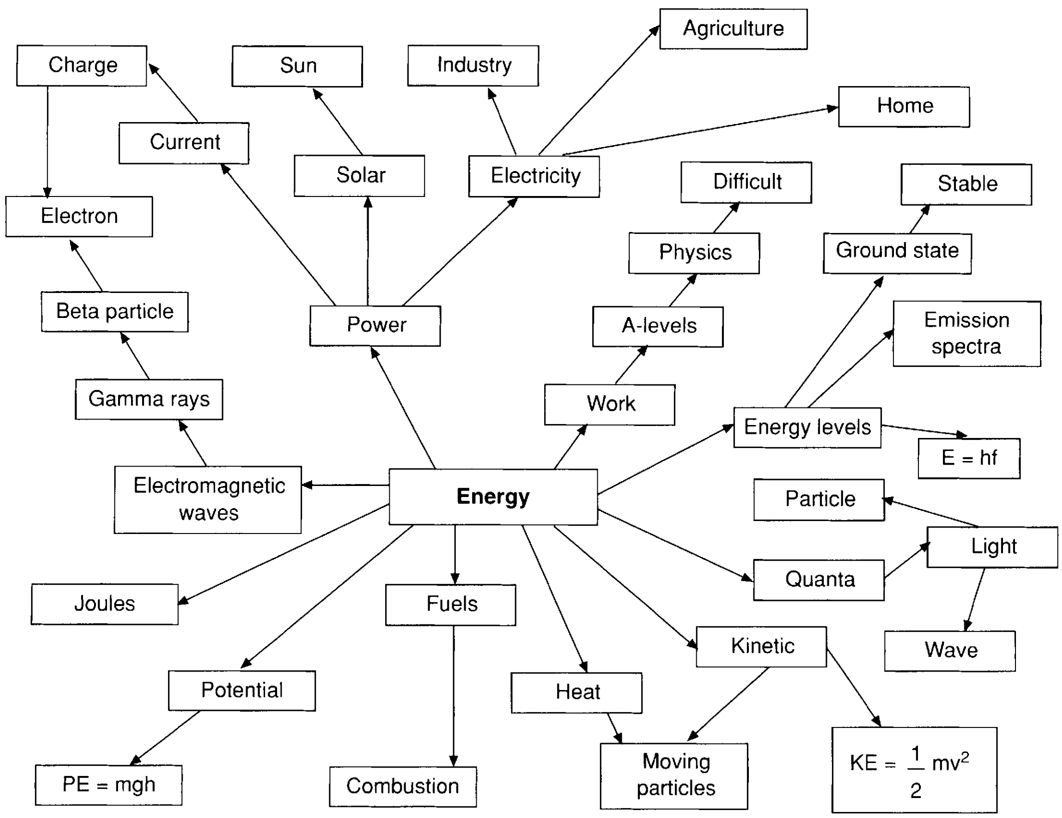

Figure 3.6 A student's concept map for energy[23]

Figure 3.6, whilst admittedly based on a (post-16) college student's concept map and not a younger student, certainly shows that students can link ideas effectively. We need to look elsewhere to explain why people should hold multiple versions of a concept. There are in fact good theoretical reasons to expect this.

For one thing, it seems that during evolution humans developed discrete 'domains' of knowledge related to the living world (thus the 'natural kinds' concepts for trees and animals discussed in Chapter 2); mechanics (thus the 'intuitive physics' in contradiction to Newton's laws) and social-psychology (enabling us to use our own feelings to model the feelings of others, and 'read' their minds from body language *etc*).[24] If this theory is correct, some compartmentalisation of our knowledge, with the possibility of forming multiple representations of some topics, is just 'human nature'.

Indeed, one explanation for how humans became so intelligent (compared with most other species) is that we developed the ability to take an idea, and mentally copy it, and adapt the copy to give a new idea, that is we developed the ability to think in terms of models and analogies![25]

This ability is essential to science. For example, all major scientific advances require someone to see ideas in a new way – for example, to see combustion in terms of reacting with oxygen rather than releasing phlogiston. Our internal 'conceptual construction kits' have an important advantage over mechanical construction kits. When scientists form a new theoretical approach they do not have to dismantle their previous understanding to use the same components in the new theory. Rather they build a new, separate, mental model, while still using the old one until the new one looks more promising (see Chapter 10).

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This ability is especially important in chemistry where we have many different models of major concepts like the atom, acids, oxidation *etc*. The scientist, and the learner, is able to use these multiple models because our brains are able to hold alternative versions of the same concepts concurrently.

The downside of this ability is that the learner does not always realise that she holds manifold conceptions or multiple frameworks, and so may not consciously select the most appropriate version to use in a particular context. A student who holds a scientifically sophisticated and 'correct' version of a concept will still sometimes produce an answer to a question using an alternative conception (see Chapter 8, Figure 8.20). 'Knowing' the 'right' answer does not imply knowing only the right answer. It is therefore important to test students' knowledge in a range of contexts.

Where we are trying to move students away from their alternative conceptions to more scientific ones, we may find that they 'relapse' in contexts that are especially familiar (where they habitually use their alternative conception) or where there is a high 'cognitive demand' due to the complexity of the problem (where a different aspect of the question may take their attention). This can be frustrating for teacher and student – and being told that such multiple representations may well be the basis of our intelligence may not seem reassuring to either!

Concept maps as diagnostic tools: eliciting knowledge structures

In view of this complexity that is characteristic of our knowledge structures, standard tests offer only a limited insight into student understanding. Even the probes in the companion volume are mostly focused on eliciting specific isolated conceptions (albeit ones which are common, and related to key topics). The best way to find out if a student really understands a topic is probably to spend extended periods of time interrogating them individually. Apart from being potentially intimidating for the student, this is an approach that teachers can seldom use due to time constraints.

A more time-efficient, and less stressful approach, is to ask students to prepare a concept map of their understanding of a topic. A concept map can reveal:

- which key ideas are present/missing;
- whether the student holds major alternative conceptions;
- how well the student has integrated ideas within the topic; and
- the extent to which the student links the concept with key ideas from related topics.

Introducing concept mapping

Before students can be asked to produce concepts maps they need to appreciate the idea of a concept map itself. Some students are likely to have met concept maps and related diagrams ('spider diagrams',[26] 'mind maps'[27]) before – but in some classes this will be a novel idea to at least some students. It is not appropriate to expect students to cope with the demands of a new way of representing information, and to think deeply about the topic to be mapped, so some familiarisation or practice will be needed.

There are various ways of approaching this:

1. the teacher might use and present her own concept maps (or examples from other classes, books *etc*) in teaching for quite some time before asking the students to produce their own;
2. students can initially be asked to produce practice maps on topics of choice (*eg* Manchester United; current fashion...) where the focus is on technique rather than content;
3. the teacher can lead class mapping of concepts with each student asked to suggest an addition to the map on the board/screen before asking students to produce group or individual maps;[28] and
4. the students can be provided with structured tasks using partially prepared concept maps, before producing them from scratch.

This final approach, of 'scaffolding' (see Chapter 5) the task, can be done in a number of ways. Here we will briefly consider two examples that have been tested in schools.

A concept map for acids at lower secondary level

This task, **Revising acids**, was based around the concept map for acids produced above as Figure 3.5. The task was differentiated to place three levels of demand on the students. The most difficult level provided students with an outline map, with only the concepts shown (Figure 3.7):

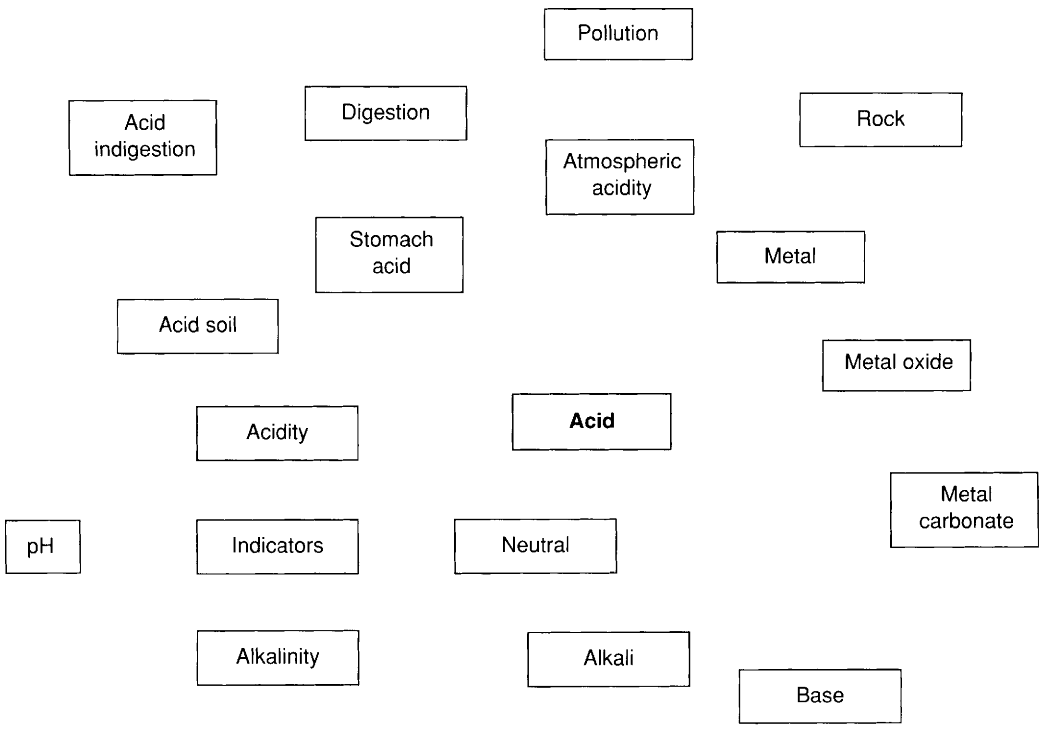

Figure 3.7 A partial concept map for 'acid'

The instructions for the students show them how to develop the map by adding connections.

When this exercise was carried out in schools to pilot the materials, it was found that some students were certainly able to make relevant and sensible suggestions for the logical connections between concepts (*eg* see Figure 3.8).

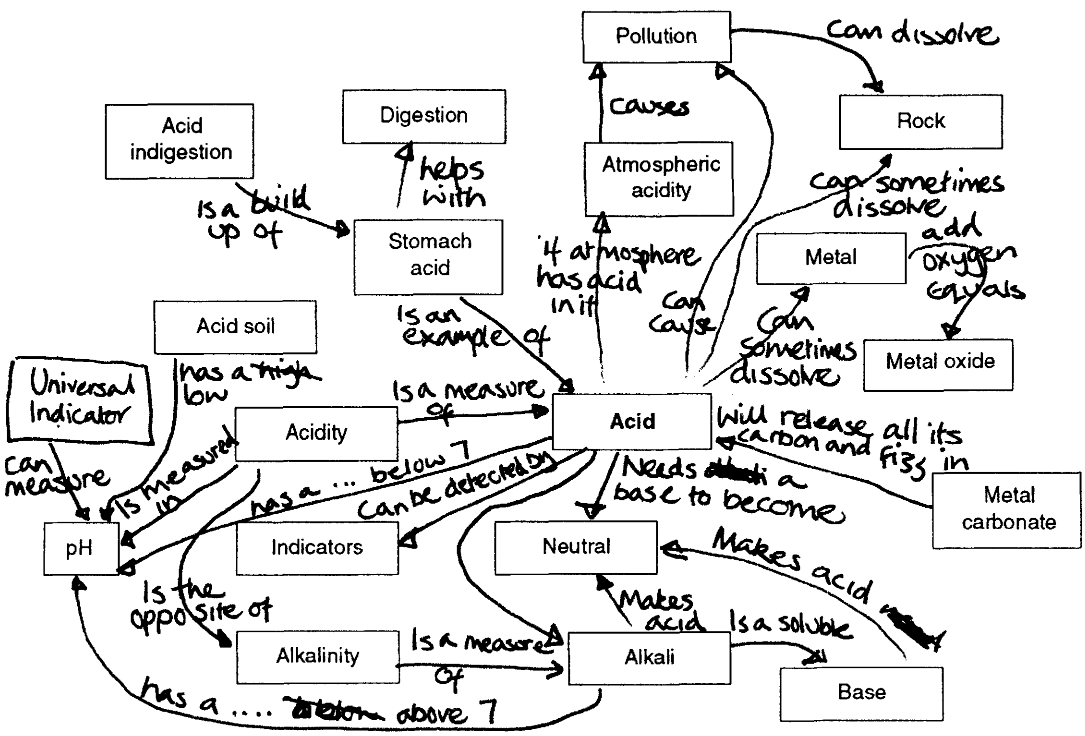

Figure 3.8 An example of a student's completed concept map

Although students may well miss some significant connections, and may use less precise or technical phrasing than the teacher would prefer (compare Figure 3.8 with Figure 3.5), they can also demonstrate considerable knowledge and understanding. (And, as after any learning activity, the teacher may provide students with a copy of a model answer – and this is likely to be more valuable once the students have made efforts to work through the ideas themselves.)

The example map shown above is from a student in a group of 12–13 year olds. This individual added a new concept - 'Universal Indicator'. Other students in the group added other concepts such as 'salts', 'acid rain', 'calcium carbonate' (connecting 'metal carbonate' to 'rock'), 'carbon dioxide', 'hydrogen', 'water', and 'phenolphthalein'.

As well as adding new concepts to the map, students may also suggest valid connections which were not expected. For example, among the suggested links from a student in a group of 13–14 year olds were:

- digestion – pollution ('produces methane');
- pollution – metal ('produces smoke when extracting'); and
- metal carbonate – metal oxide – metal ('product of extraction').

Of course, student responses may also suggest they hold alternative conceptions. A student in the same group of 13–14 year olds proposed that an acid 'can be a base dissolved in water'

A less demanding version of the task provided an outline map with connections between the concepts (see Figure 3.9), and a separate list of incomplete statements representing the links (*eg* 'A. Acids in the ______________ cause atmospheric acidity.') The students had to identify the links by labelling the connections on the map (as 'A' *etc*), and complete the statements.

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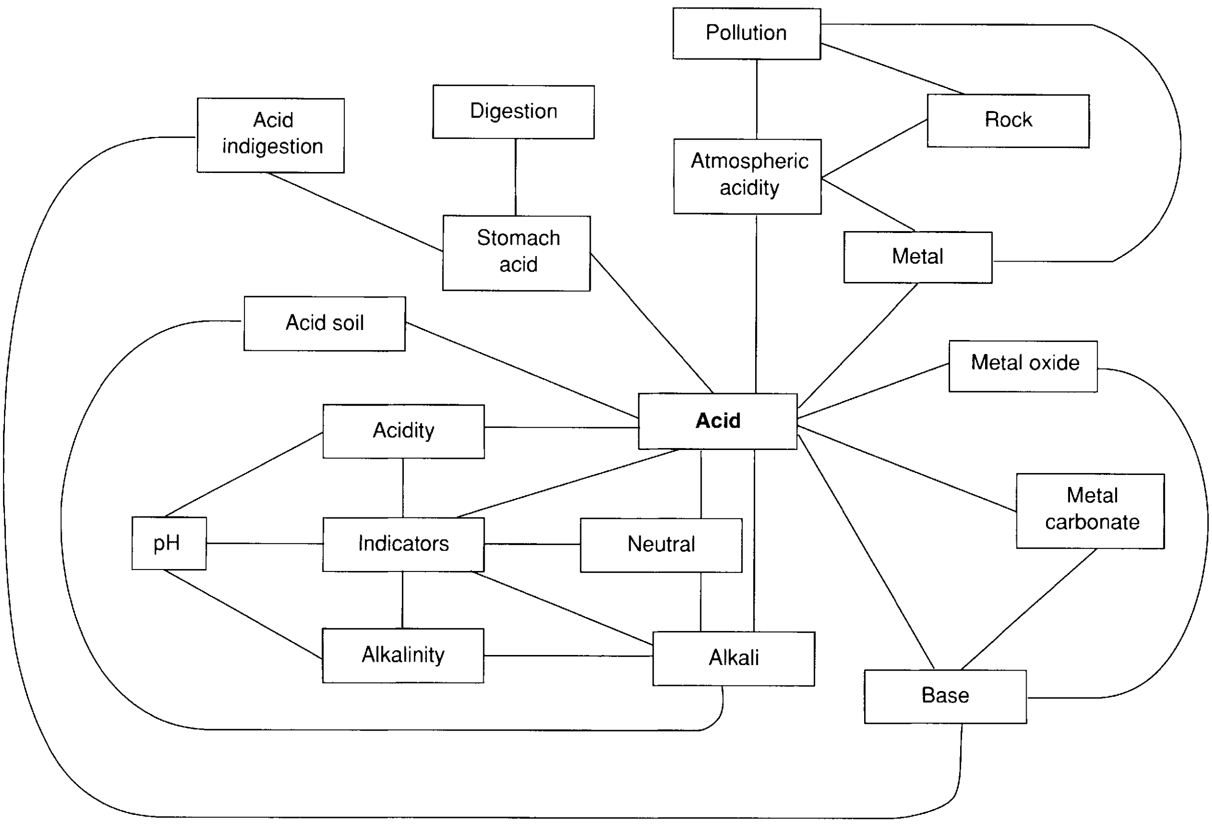

Figure 3.9 An outline concept map for 'acid'

A final, least demanding, version of the task provides the same map (see Figure 3.9) and the same list of statements, but this time complete (*eg* '1. Acidity is a property of acids'), so the student merely has to label the connections ('1' *etc*).

When the materials were used with classes some teachers felt that the least demanding version of the exercise was too simple, as it required no real knowledge of chemistry to complete. This was intentional, as it provides a task which only requires reading skills to complete, and so could be attempted with some success by a student who had learnt little about the topic (and could actually lead to some learning along the way – see the comments about DARTs, Directed Activities Related to Text, in Chapter 5).

The teachers setting this exercise were quite correct in their characterisation of this version of the task. However, the responses of some of the students asked to complete the intermediate version suggests that some teachers may have under-estimated the demand of the task (or overestimated the knowledge of the students) in deciding how to assign the three versions of the exercise. The following suggestions are some of the responses offered from 13–14 year olds in one class – the words in bold are those added by the student to complete the statement: [29]

- Acids in the ***metal*** cause atmospheric acidity.
- ***Rock*** can increase the rate of weathering of rocks.
- Atmospheric acidity causes the corrosion of some ***rocks***.
- Too much stomach acid can cause ***digestion***.
- Too much stomach acid can cause ***hydrogen***.
- Some ***pH*** contain too much acid for many plants to grow.

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- Bases react with *alkali*.
- An *salt* is a base which dissolves in water.
- An *metal* is a base which dissolves in water.
- An *oxid* [sic] is a base which dissolves in water.
- Metal oxides are *acids*.
- Metal oxides react with *bases* to give salts and water.
- Metal oxides react with *alkalis* to give salts and water.[30]
- Metal oxides react with *metals* to give salts and water.
- Some *bases* react with acid to give a salt and hydrogen.
- Alkalinity is a property of *acids*.
- Neutral solutions can be identified using *acid*.

Perhaps some of these students would, in hindsight, have been better assigned to the least demanding version of the exercise.

A concept map for the Periodic Table at upper secondary level

Another concept map exercise, **Revising the Periodic Table**, prepared for this publication used a slightly different approach. This was a concept map on the topic of 'the Periodic Table' intended for upper secondary level students.

The students were provided with a concept map with labelled links (see Figure 3.10), and given a sheet to suggest sentences relating to the links. One example was completed for them ('6. An element is a single chemical substance') and they were asked to complete sentences for as many of the links as they could. This task is more demanding than two of the levels of the 'revising acids' exercise (which was intended for younger students), and differentiates by outcome, in terms of the sophistication of the responses students can make.

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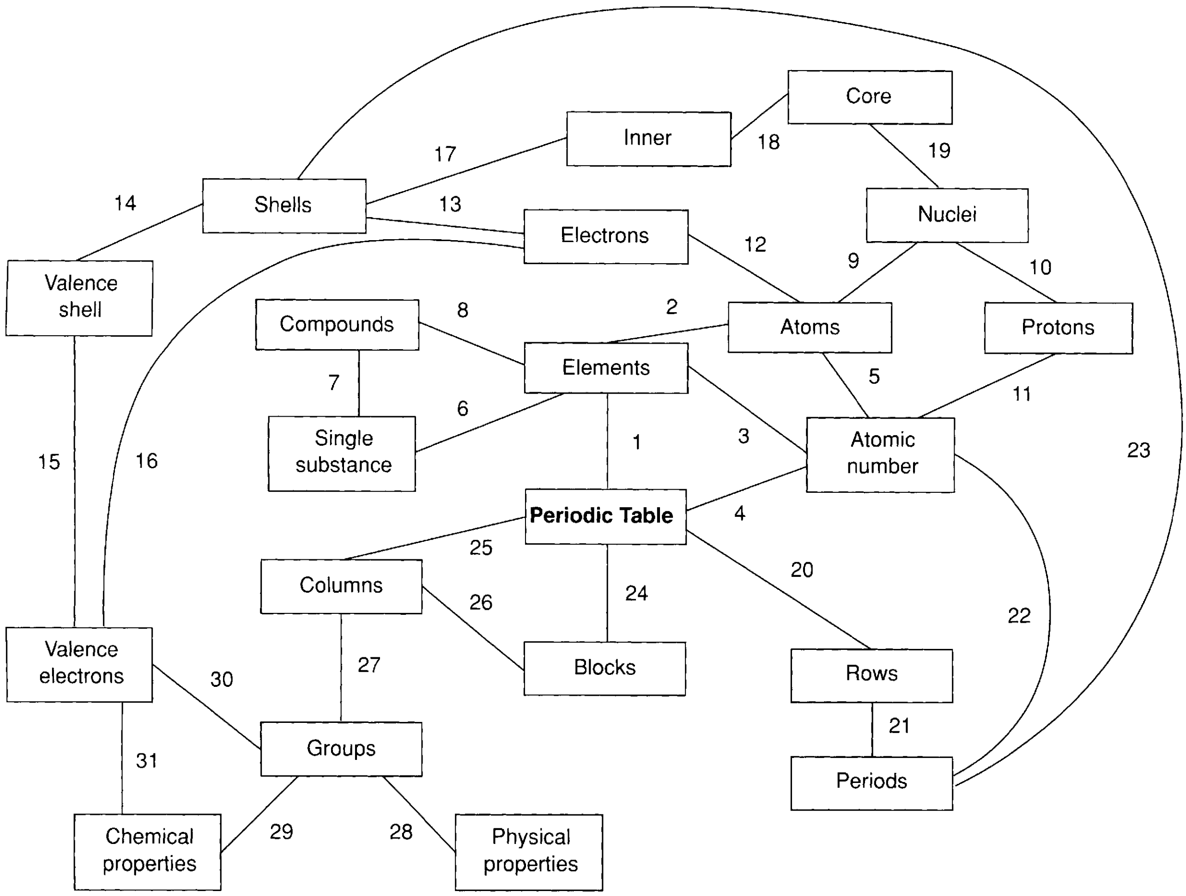

Figure 3.10 A concept map for 'the Periodic Table'

When this exercise was piloted for the project is was found that this format was helpful in allowing students to demonstrate their learning, and many sensible and valid responses were given. This type of exercise might be seen as providing a structure or 'scaffold' to help students explore and utilise their knowledge (see Chapter 5).

The format also provided examples of student statements which were unclear, ambiguous or wrong. The following statements are examples from two groups of 15–16 year olds:

- 'The Periodic Table has many different blocks, each with an element in.'
- 'The shell of electrons wants to be full. If not it is more reactive.'
- 'A compound is not a single chemical substance.'
- 'All elements are atoms.'
- 'An element is a single substance, a compound is more than one.'
- 'An atomic number shows the number of atoms.'
- 'Atoms are another name for the same element.'
- 'The amount of valence electrons depends on the chemical properties.'
- 'The outer shell should contain 8 electrons to be full.'
- 'There will be protons (the same number of neutrons) in an element.'
- 'Protons go round the nuclei'.
- 'The protons + electrons = atomic number'

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These statements include the vague ('All elements are atoms'), and the sometimes-correct ('The outer shell should contain 8 electrons to be full' - only true for period 2) as well as the simply wrong ('A compound is not a single chemical substance'). Some statements may represent difficulty in expressing an idea. Perhaps 'the amount [*sic*] of valence [*ie* outer shell] electrons depends on the chemical properties' was meant to imply that the number of outer shell electrons determines the chemical properties. Maybe the statement that 'the protons + electrons = atomic number' was intended to imply that the number of protons equals the atomic number, and also that the number of electrons, equals the atomic number.

Whether such statements reveal genuine alternative conceptions, or limited language skills, or even just guessing in some cases, such responses reveal to the teacher areas where some attention is needed to check the student understands and can express the scientific idea.

Some alternative conceptions may derive, at least in part, from linguistic cues (the way the same or similar words are used in everyday life), or from some quirk in the way the a particular teaching scheme has been constructed. (These ideas are discussed in more detail in Chapter 4.)

However, often it is found that similar alternative conceptions are elicited from students in different education systems, even when the language of instruction is different. Marinella Spezziga, a teacher in Italy, translated the classroom materials discussed above, **Revising the Periodic Table**, into Italian, and presented them to her class of a similar age to the UK students. Marinella found some similar confusions and alternative conceptions among her students as have been elicited when the materials have been undertaken in English. As in the UK, some Italian students were unclear about the meaning of the terms substance and atomic number, the relative arrangement of sub-atomic particles, and the relationship between molar properties and atomic structure,[31]

- 'The combination of two or more elements is called substances'
- 'The atomic number is the number of atoms of an element'
- 'The atoms are found in the nucleus'
- 'Protons spin round nucleus'
- 'The electrons in the outermost shell have got the same properties'

There is a striking parallel between some of these suggestions, and those made by the UK students (reported above).

The materials discussed here, **Revising acids** and **Revising the Periodic Table**, illustrate two ways that concept mapping tasks may be set. There are other permutations on presenting incomplete concept maps. For example, a student could be given a list of propositions and asked to draw a concept map from them,[32,33] or given a nearly complete map with a few key concepts blanked out.

Concept maps as learning tools: learning styles

In many classes there will be some students who do not like, or even see the point, of concept mapping. Other students, however, are likely to find concept mapping activities enjoyable and useful.

We all have different preferred ways of learning (and teaching!), and just as some students feel they learn more by listening, and others by reading, some will prefer normal ('linear') textual materials, where others prefer more graphical (diagrammatic) ways of representing ideas.[34,35,36,37]

We need a lot more research about how important different 'teaching/learning/thinking styles' are in learning science, and what teachers should do to meet the needs of students with different ways of learning.

However, even without such research, there are a number of arguments for teachers incorporating techniques like concept mapping into their teaching. Given that it is likely that different students learn better from different approaches, then a teacher who uses concept mapping (along with flow charts and other forms of diagrams) as well as normal ('linear') text will:

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- be more likely to match up with different students' needs through the variety of approaches; and
- help familiarise learners with a range of approaches to help them find their preferred ways of learning.

In addition:

- different information is best represented in different formats; and
- multiple formats for the same information provide reinforcement and redundancy without obvious repetition. (See the comments on DARTs in Chapter 5.)

Finally, students learn best when they actively process information rather than passively receive it. Tasks that require students to translate information from linear texts to concept maps, or from flow charts to linear texts (for example) mean that the learner is actively involved in the task, is empowered to succeed (as the information is given, and just needs processing), and is working with the accepted version of the concepts (rather than just relying on existing understanding, which may include alternative conceptions).

An example of an activity which asks for such a 'conversion' is the exercise **Explaining chemical phenomena** (included in the section on **Scaffolding explanations** in the companion volume), where college students are asked to complete chemical explanations. Partial explanations are provided in flow chart form, which once completed need to be translated into linear text (see Chapter 5).

Concept maps as revision tools: metacognition

'Metacognition refers to a person's knowledge about his or her cognitive abilities[38]'

A final point about concept mapping is that it is a technique which can help students take responsibility for their own learning. Although the teacher may well feel that lower secondary students need a great deal of guidance, it seems appropriate to help students learn good study habits as early in their studies as possible. School sixthformers, college and undergraduate students are expected to take increasing responsibility for planning and executing their own study programmes, and those who leave school or college as effective self-directed learners will have an edge over those requiring 'spoon-feeding'.

This becomes especially important in terms of revision. Teachers can usually advise students on the progress of their work, but this is more difficult when students are revising, especially where the school or college gives study leave. Different students spending the same amount of time revising for a test may well use that time very differently. For those who tend to just read through their notes, there may be little awareness of how (in)effective their revision is until too late (*eg* the test). Where students can be encouraged to think about their own learning processes and develop an overview of their learning, they will have an advantage.[39]

The term 'metacognition' (being aware of one's own thinking processes – thinking about thinking)[40] may suggest a very high level skill, but can be practised in quite rudimentary ways. It is useful to encourage students to monitor their own progress and learning, rather than relying on external evaluation. Some revision activities are more likely to encourage such reflection than others. Students who are familiar with concept mapping may use it as a technique to test their knowledge of topics while revising, and may find it is a very helpful technique to help them judge their own progress:[41]

'My knowledge ... is very un-organised at present'

'I didn't realise how much the different areas inter-linked'

'I think this exercise was useful as it let me know exactly how much I know about [the topic], which I can now see is not enough'

Unlike some other activities, the non-linear nature of concept mapping allows the learner to move from working on one part of the map (if 'stuck') to others, and is an activity which inherently emphasises the structure of the subject:

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'Quite useful, brings back memories; good to see how well topics relate or how well you can interrelate them'

'I found I was digging around, trying to put fragments of things I could remember together. I found I could remember only scraps of information, but when doing the drawing [*ie* concept map], saw how things pieced together, and linked with other things'

'At first I did not know where to start but as I began putting ideas down, it reminded me of other points. I could have carried on writing'

'I didn't realise how much the different areas inter-linked. You could go on and on forever. I think this is a very pleasant experience and something I shall intend to continue doing.'

In any class there are likely to be some students who do not enjoy concept mapping activities (just as there are some who do not like producing written accounts, some who dislike calculations and others who prefer not to have to draw diagrams). Yet many students will enjoy and value the approach, and it certainly provides an alternative to formal note-taking. Moreover, it is a flexible technique – which can be used by teachers, individual students or groups; and as a tool for planning, for diagnosing understanding, as a learning activity or a revision technique. It is also a format closer to knowledge structures than the more usual text produced by teacher and student.

Notes and references for Chapter 3

1. B. Murphy, C. Murphy & B. J. Hathaway, *Basic Principles of Inorganic Chemistry: Making the Connections*, Cambridge: Royal Society of Chemistry, 1998.

2. H-J. Schmidt, Should chemistry lessons be more intellectually challenging?, *Chemical Education: Research and Practice in Europe*, 2000, **1** (1), 17–26, available at **http://www.uoi.gr/conf_sem/cerapie/** (accessed October 2001).

3. One new approach to thinking about, and teaching, chemistry argues that 'the division of reaction chemistry into organic and inorganic is anachronistic and confusing' (note 4) and suggests that reactions be studied instead in the categories: redox chemistry; photochemistry; Lewis acid/base chemistry; radical and diradical chemistry. This approach is aimed at University level study, but is an interesting example of an attempt to reconceptualise the patterns of the subject. More information may be found at **http://www.meta-synthesis.com** (accessed October 2001).

4. M. R. Leach, *Lewis Acid/Base Reaction Chemistry*, Brighton: Meta-Synthesis.Com, 1999, 5.

5. For a recent survey of the frontiers of chemical science, see T. Lister, *Cutting Edge Chemistry*, London: The Royal Society of Chemistry, 2000.

6. W. B. Jensen, *Logic, History and the Teaching of Chemistry*, text of the Keynote Lectures, given at the 57th Annual Summer Conference of the New England Association of Chemistry Teachers, Sacred Heart University, Fairfield, Connecticut, 1995.

7. B. Earl & L. D. R. Wilford, *Further Advanced Chemistry*, London: John Murray Publishers, 2001, 201–207.

8. A. Al-Kunifed & J. H. Wandersee, One hundred references to concept mapping, *Journal of Research in Science Teaching*, 1990, **27** (10), 1069–1075.

9. J. D. Novak, Concept mapping: a useful tool for science education, *Journal of Research in Science Teaching*, 1990, **27** (10), 937–949.

10. J. H. Wandersee, Concept mapping and the cartography of cognition, *Journal of Research in Science Education*, 1990, **27** (10), 923–936.

11. B. Ross & H. Mumby, Concept mapping and misconceptions: a study of high-school students' understandings of acids and bases, *International Journal of Science Education*, 1991, **13** (1), 11–23.

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12. K. S. Taber, Student reaction on being introduced to concept mapping, *Physics Education*, 1994, **29** (5), 276–281.

13. A proposition can be defined as 'The smallest unit of knowledge that can stand as a separate assertion; that is, the smallest unit about which it makes sense to make the judgement true or false' – J. R. Anderson, *Cognitive Psychology and its Implications (4th Edition)*, New York: W. H. Freeman & Co, 1995, 145.

14. However, note that this does not imply that something is a concept only when you give it a name. Concepts may be 'tacit' - categories that we are aware of, and apply, at some level without being consciously aware that we are using them. All of our early concepts start of like this – we are able to make discriminations before we have any use of language, even though language, once acquired, becomes the key tool for learning, refining and exploring concepts.

15. In the English National Curriculum there are in-built opportunities to revisit many topics at successive stages. This has been criticised by some teachers who report that students find the curriculum repetitive. This should not be the case if each time a topic is met there is a brief recap of prior learning, and then significant progression in terms of the way the topic is developed. Teachers need to find different examples, and ways of presenting information, to ensure that students do not experience review as simply repetition. The QCA scheme of work *Science, A scheme of work for Key Stage 3*, QCA, 2000, may be useful in this respect, and the ideas about DARTs in Chapter 5 may also be helpful.

16. D. M. Gower, D. J. Daniels & G. Lloyd, Hierarchies among the concepts which underlie the mole, *School Science Review*, 1977, **59** (207), 285–299.

17. M. L. Starr & J. S. Krajcik, Concept maps as a heuristic for science curriculum development: towards improvement in process and product, *Journal of Research in Science Teaching*, 1990, **27** (10), 987–1000.

18. This definition from recent research (note 19) is an amalgam of ideas from two separate sources (notes 20 and 21).

19. K. S. Taber, Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure, *International Journal of Science Education*, 2000, **22** (4), 399–417.

20. D. P. Ausubel & F. G. Robinson *School Learning: An Introduction to Educational Psychology*, London: Holt International Edition, 1971.

21. R. T. White, Interview protocols and dimensions of cognitive structure, in L. H. T. West & A. L. Pines, *Cognitive Structure and Conceptual Change*, London: Academic Press, 1985, 51–59.

22. G. Claxton, Minitheories: a preliminary model for learning science, in P. J. Black & A. M. Lucas, *Children's Informal Ideas in Science*, London: Routledge, 1993, 45–61.

23. K. S. Taber, Student reaction on being introduced to concept mapping, *Physics Education*, 1994, **29** (5), 276–281.

24. It is deficits in this area which lead to autism.

25. A. Karmiloff-Smith, Précis of Beyond Modularity: A developmental perspective on cognitive science, *Behaviour and brain Sciences*, 1994, **17,** 693–745.

26. P. A. Wood, Spider diagrams, *School Science Review*, 1981, **62** (220), 550–553.

27. T. Buzan, *Use Your Head (Revised Edition)*, London: BBC Worldwide, 2000.

28. It is advisable to select a topic which everyone knows something about and feels they can contribute something. In introducing concept mapping with one class the central concept was 'blood' and 'blood is red' was accepted as a valid contribution. At this familiarisation stage it is the technique which is central, not the degree of insight produced.

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29. National tests in England have shown that students at this age 'often fail to distinguish between the different substances with which [acids] react, metals, carbonates and alkalis/bases, and to identify the products of these reactions', Qualifications and Curriculum Authority (QCA), *Standards at Key Stage 3 Science*, London: QCA, 2001.

30. Students at this age are unlikely to have met the notion of amphoteric metal oxides which react with alkalis as well as acids.

31. Thanks are due to Marinella for re-translating the student responses back into English to share her findings.

32. T. Hudson, Developing pupils' skills, in M. Atlay *et al*, *Open Chemistry*, London: Hodder & Stoughton, 1992, 143–160.

33. W. Harlen, *The Teaching of Science*, London: David Fulton Publishers, 1992.

34. R. J. Sternberg, *Thinking Styles*, Cambridge: Cambridge University Press, 1997.

35. B. S. Thomson & J. R. Mascazine, Attending to learning styles in mathematics and science classrooms, 1997, at **http://www.ericse.org/digests/dse97-4.html** (accessed October 2001).

36. H. Gardner, M. L. Kornhaber & W. K. Wake, *Intelligence: Multiple Perspectives*, Fort Worth: Harcourt Brace College Publishers, 1996.

37. R. Riding & S. Rayner, *Cognitive Styles and Learning Strategies: Understanding Style Differences in Learning and Behaviour*, London: David Fulton, 1998.

38. A. D. Pellegrini & D. F. Bjorklund, *Applied Child Study: a Developmental Approach (3rd Edition)*, Mahwah, NJ: Lawrence Erlbaum Associates, 1988.

39. C. Chin & D. E. Brown, Learning in science: a comparison of deep and surface approaches, *Journal of Research in Science Teaching*, 2000, **37** (2), 109–138.

40. Gunstone and Mitchell break metacognition down into metacognitive knowledge (about learning in general and about one's own personal learning characteristics), metacognitive awareness (of the purpose of, and progress in, a particular learning context) and metacognitive control (relating to the decisions and actions taken during a particular learning activity): R. F. Gunstone & I. J. Mitchell, Metacognition and conceptual change, in J. J. Mintzes, J. H. Wandersee & J. D. Novak, *Teaching Science for Understanding: A Human Constructivist View*, San Diego: Academic Press, 1988, 133–163.

41. The quotes are taken from K. S. Taber, Student reaction on being introduced to concept mapping, *Physics Education*, 1994, **29** (5), 276–281.

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