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

RS•C

1. Alternative conceptions in chemistry teaching

This chapter provides a brief introduction to the topic of learners' ideas in science, and in particular to the types of alternative conceptions that have been uncovered among chemistry students in schools and colleges.

Students' alternative ideas

Water turns blue when copper sulfate is added:

'because the copper sulfate has a chemical inside it that turned the water blue'
a student in class of 11–12 year olds

A compound is:

'a substance that contains 2 or more of the same kind of atom'
a student in a class of 13–14 year olds

Hydrogen reacts with fluorine:

'because fluorine wants to gain an electron and hydrogen wants to lose one'
a student on post-16 course

The above comments were made by students responding to probes that are included in this publication. These comments, and many others like them reported in the research literature, show that students often develop alternative ideas about the science they are taught in school.

What learners don't know about science

Nobody is very surprised that when students are asked questions about science topics which they are meant to have studied, they often give 'wrong' answers. If matters were otherwise then presumably students would all score 100% on tests, and there would be no need for science teachers to be highly skilled classroom practitioners (and little need for the tests either). This much is true in other subjects as well as science, and may be explained in a number of ways. Assuming students were actually in the lesson when material was taught then they may not have been paying attention; or they may have not understood what the teacher said; or they may have just forgotten. As we are all sometimes guilty of not paying attention; and there are times when we do not understand what is said to us; and as we all sometimes forget things we wanted to remember, this may seem to be explanation enough.

Teachers are usually aware when students are not paying attention, and respond accordingly. Teachers also have ways of finding out when learners do not understand. In an ideal world we create the type of supportive learning environment where students are keen to learn, take responsibility for asking when unsure, and are confident to speak up without feeling self-conscious or in danger of ridicule.

Even when our classrooms and teaching laboratories do not match this ideal, teachers learn to use questioning techniques to check learners' understanding.[1] As effective learning requires regular reinforcement and review, forgetting is a more difficult problem for the teacher to tackle, particularly where there is much material to cover and classes are not seen frequently. However, even in this area, teachers can take every opportunity to bring in previous work and relate this to new topics, and can encourage effective study skills in their students.

No doubt such professional techniques are very useful, but – even with the improvements they may bring – we do not expect all the class to get near perfect marks on the end of topic tests.

RS•C

What learners think they know about science

What may be more surprising than students' failures after teaching are their responses when they are asked questions about science topics before they have covered the work. Clearly students are less likely to produce acceptable scientific responses before teaching than afterwards. (It would be very worrying if this was not the case.) What is less obvious is how often the learner is able to produce some kind of answer to scientific questions before they have (formally) learnt anything about the topic.

Of course sometimes youngsters may just feel they ought to think of an answer because of the social pressure of being asked by an adult.[2] The influential Swiss psychologist Jean Piaget described how young children would often 'romance' up an answer when they were asked something that they did know about.[3] However, research evidence suggests that many of the answers that students produce cannot be explained in that way and there is a great deal of research evidence available to consider.

Over the past twenty years there has been a vast research effort to ask students all sorts of questions about many different science topics - before, during and after teaching. There are now thousands of papers in research journals and conference proceedings presenting the results of this research, and a range of books discussing the findings.[4] In view of the great diversity of this work (undertaken in the UK, New Zealand, Australia and many other countries; with learners of various ages from young children to graduates; and in aspects of biology, physics and chemistry) it is not surprising that the 'experts' do not all agree on all the details of what this research tells us. However, there is a general consensus on many important points, and it is certainly agreed that learners hold a wide range of ideas about many scientific topics – ideas that often contradict the science they will meet in school and college.[5]

Students as scientists?

It is certainly very clear that teachers can not safely assume that their students will come to classes without any preconceived ideas about a topic, giving the teacher a 'blank slate' on which to impress scientific knowledge.

The late Rosalind Driver (who was very influential in undertaking and encouraging research into learners' ideas) described 'the pupil as scientist', and explained that from a young age children behave like amateur scientists, finding patterns in the world and forming conjectures to explain these patterns.[6]

Of course, the youngsters are not professional scientists, and so their thinking does not always match scientific standards.[7] The important point was that by the time a student comes to secondary science he or she will have built up a great many of their own explanations about the way the world works, and many of these will be at odds with the scientific view. (The student will also have studied science in primary school, but may well – despite having being given satisfactory explanations – have misinterpreted that teaching in the terms of their prior conceptions).

One way in which Driver found that students were rather poor scientists was in the way they treated data. Driver found that students were often unable to see that the results of an experiment should have refuted their ideas about what was going on. Indeed, she found that often students would 'see' and record what their preconceptions told them to expect to see – and so their recorded results matched their expectations rather than what they were meant to observe. (If one wished to be cynical one might suggest that Driver got her slogan wrong – and that her book should have been called 'the pupil as politician', 'the pupil as Freudian analyst' or 'the pupil as Marxist historian'.)

The important point that Driver recognised was that this failure to record results accurately was not due to laziness, or stubbornness or being deliberately awkward. Students were not being arrogant – just human. Driver's observations reflected something very important about the human perceptive system: we often see what we expect to see rather than what is in front of our eyes. From a physiological point of view we do not see with our eyes, but with our brains, and the signals from the

RS•C

eyes are only part of the information being used to make sense of the world. This can be seen by referring to one of the books presenting optical illusions,[8] which show how our brains attempt to interpret what we see in terms of the patterns we expect.

Professional scientists receive training in applying practical and analytical techniques to help them learn to give precedence to the data, and to be (less) biased by their expectations in experimental work. Students in school are only just starting out on their training in scientific method.

The nature of learners' ideas

The research into learners' ideas about scientific topics suggests that students' informal ideas vary across a number of dimensions. Some of the ideas reported appear to be quite specific, whilst others appear to be more general. Sometimes learners' ideas are quite labile, and are readily changed, but others may be very stable, and quite tenacious in the face of instruction.[9] Some of the ideas reported seem to be fairly isolated and not particularly well related to the students' other ideas, whereas some ideas seem to be embedded in complex, coherent, logically related structures.

Certain researchers who have worked in the field have suggested that because some of the alternative ways of explaining science revealed in research have seemed to be loosely associated clusters of ideas or logically incoherent, then learners' ideas are always like this.[10, 11] In my own research I have found that learners' thinking can be very variable. Students, like any of us, can have strongly held beliefs, as well as vague notions, and relatively isolated ideas as well as logically developed frameworks of conceptions.

The advice I would give to teachers can be summarised in three points:

1. In any class, for any science topic, students are likely to hold a wide range of alternative ideas about the topic;
2. not all of these ideas will be highly significant in terms of impeding the intended learning; but
3. some of them will.

Therefore, teachers need to take learners' ideas seriously.

The significance of learners' ideas

Some of the ideas that students will bring to class will just appear to 'evaporate' away once the scientific perspective is presented. However, this is certainly not always the case. Indeed there are a number of possible outcomes when a student (holding one set of ideas) is taught science which is inconsistent with their prior conceptions;[12]

1. Sometimes the new learning does seem to successfully supplant the old ideas without too many problems.
2. Sometimes the learner treats the new ideas as if they are unrelated to their previous thinking. The science that has been learnt in school seems to be 'stored' separately from the existing ideas. Sometimes when this happens the student may use one set of ideas to answer formal science questions, but a different set of ideas in everyday situations.

This research suggests that when the same scientific principle is tested in an abstract 'scientific' context, it will be answered differently to an equivalent question testing the same principle, but set in a novel everyday context.[13, 14, 15, 16, 17] This may have consequences for examiners looking to set questions in novel everyday contexts,

'[A] question on differences between the element iron and its compounds... set in the context of breakfast cereal content was... [often] answered using everyday understanding rather than scientific knowledge, for example stating that iron is inedible, whereas iron compounds are edible.'[18]

Some science educators feel it is satisfactory for learners to acquire separate versions of scientific ideas which they apply in academic and everyday (or 'life-world') contexts, and some students seem to be able to successfully retain workable versions of the ideas in both of these 'domains'.[19, 20]

3. However, it is often found that when the student stores the new ideas separately they are soon forgotten. Although tests shortly after the teacher's presentation may be encouraging, it is sometimes found that re-testing weeks and months later leads to the student returning to their original way of thinking about the topic.[21] This is disappointing as the learning that occurs appears to have been rather superficial (and does not survive to end of course examinations, let alone through later life). Indeed it may be found that experiments that were presented to demonstrate the scientific ideas are now recalled as having different results – results which support the students' original way of thinking about the topic. Retrieval of information from memory is known to be a reconstructive process, where much of a 'memory' is often inferred from specific items of recall.[22,23]

4. Sometimes little or no learning takes place because the learner is unable to make sense of the teacher's presentation in terms of their existing ideas. In this case the learner's ideas may seem unchanged by the lesson.

5. Sometimes the learner is able to make sense of the teacher's presentation in terms of their own alternative way of thinking about the topic. This may result in the student learning new material, but not in the way intended. The learner unintentionally distorts the teacher's words to fit into the existing framework. Often, when this happens, neither the teacher nor the student are aware that the student is reinterpreting the material in this way – at least not until the new learning is elicited in a test.

This may mean that there is no *fundamental* change in the way the learner understands the topic, despite new learning having taken place (as the new ideas are all made to fit with the existing understanding). However it is also possible for the process of 'making sense of the teacher' to lead to the student's ideas starting to change. The result may be a hybrid understanding of a topic somewhere between what the student started out with, and what the teacher intended.

As we all know, teaching science is a challenging and complex affair.

Describing learners' ideas

Up to this point I have deliberately been a little vague in the way I have described learners' ideas about science topics. This is because, unfortunately, experts do not agree on what terms should be used.[24]

If you read some of the journal articles and books in the Notes and references section you will find references to a whole range of terms. Students' ideas may be described as intuitive, informal, misconceived, alternative, preconceived, prior, folk, life-world, etc; they may be ideas, concepts, conceptions, frameworks and so on.

The reason why so many terms are used is (in my view) because learners' ideas are so varied. Some aspects of thinking may well reflect the structure of the human cognitive apparatus (*ie* the way nerve cells in the brain work together), and could be considered 'intuitive'. Other ideas are picked up from the social milieu – the playground, television, listening to parents and older siblings etc – and may be described as 'informal'. If a student misinterprets what a teacher has said we might call their idea a 'misconception'.

Of course, many ideas that learners have can not be so easily classified. Brain structure; early experience of the world; the quirks of language; things heard, seen and read out of school; and classroom experiences may all play a part in building up new ideas. All new learning is interpreted through existing ideas, so few notions that people have can be said to derive from just one source.

RS•C

I will refer to learners' ideas that do not match science as being 'alternative', that just means they are different, without needing to consider how they arise. (Later it will be suggested that it is useful to distinguish those alternative conceptions which seem to derive partly from the way we teach topics, to those which students seem to acquire regardless of how we teach – see Chapter 4.)

Two terms that are commonly used are 'alternative conceptions' and 'alternative frameworks'. I tend to use these terms to have slightly different meanings so that;

- alternative conception - refers to a single idea; and
- alternative framework - refers to a complex or structure of related ideas.

There are some examples given below. However, you should bear in mind that it is not always obvious whether an elicited conception is actually part of a more complex framework, and in some articles and books you will find these terms are used interchangeably, as if they are synonymous. It is less important which terms we use to describe students' ideas, than to (a) recognise that students have alternative conceptions that may interfere with learning, and (b) know how to diagnose and try and respond to them. That is what this publication is about.

Some examples of alternative conceptions

Alternative conceptions are found in all areas of science. For example, in physics, it is found that something like 85% of secondary students are likely to hold an alternative conception of the way that movement relates to force.[25, 26] It has been shown that students usually think that a continuously applied force will result in a body reaching a maximum speed, as an applied force gives an object a certain amount of 'impetus', which then somehow wears-off or dissipates. This is one of the alternative conceptions that is known to be very tenacious, and has been found to commonly recur despite instruction in Newtonian mechanics.

A common alternative conception from biology concerns the origin of the matter in plants such as trees. When people are given a piece of wood and asked how the material got into the tree they commonly reply that most of it came from the soil, although this is not the 'scientific' answer. I have seen footage of American engineering graduates and graduating science teachers in England confidently explaining that the mass of the tree came from the soil. Presumably most of these graduates would have been able to explain the basics of photosynthesis (had that been the question) and perhaps they had stored their learning about the abstract scientific process (where the carbon in the tree originates from gaseous carbon dioxide in the air) in a different compartment from their 'everyday knowledge' that plants get their nutrition from the soil.

When national UK test data was analysed by researchers for the Children's Learning in Science Project (CLiSP), it was concluded that only a third of 15 year old students used scientifically acceptable ideas about plant nutrition.[27]

Although the literature which describes alternative conceptions in science is vast, a very good (if slightly dated now) overview relating to the secondary science curriculum is available.[28]

Teachers may be able to see examples of their own students' alternative conceptions when using probes, such as **Elements, compounds and mixtures**, and others, in the companion volume to this book.

Alternative conceptions in chemistry

Chemistry is not exempt from its share of alternative conceptions. For example it has been found that it is common for post-16 students studying chemistry to think that:

- the nucleus of an atom gives rise to a certain amount of attractive force which is shared between the electrons in the atom.

This 'conservation of force' principle[29, 30] can be used (at a simple qualitative level, anyway) to 'explain' why successive ionisations require greater energy. Each time an electron is removed from an

RS•C

atom or ion the nuclear force is shared among a smaller number of electrons - so they each experience more force than before. (This is certainly an easier way of explaining the phenomena than the accepted scientific version!)

This is one example of where ideas from physics are used to explain aspects of chemistry, and it might be thought that students studying both subjects would not be likely to hold this alternative conception. However, it seems some students store their physics and chemistry learning in different memory domains, and do not easily apply their understanding about forces and electrostatics in chemistry.[31]

There are many other examples of alternative conceptions relating to chemistry topics. The Royal Society of Chemistry has commissioned a report on alternative conceptions in chemistry, which is freely available for consultation or downloading on the Internet.[32]

Consider the following examples:

- a neutralisation process always produces a neutral product;[33]
- in a nucleus the neutrons have the job of neutralising the charge on the protons;[34]
- isomers are always members of the same class of compounds (*eg* both alcohols, but not an alcohol and an ether);[35]
- a hydrogen bond is a covalent bond to hydrogen.[36]

The first example shows the importance of language in learning science. Hans-Jürgen Schmidt believes the label ('neutralisation') suggests to students that the process should give a neutral product. (The examples students meet early in their school chemistry usually do, which reinforces the idea!) A similar effect may explain why students often expect all freezing temperatures to be experienced as cold, and all melting temperatures (even for the same substances) to always be experienced as hot.[37] This effect could also be important in the second example where students are taught that a nucleus contains positive charges (which they should know will repel each other) and neutrons. The natural tendency to look for an explanation, and the suggestive label, might explain why students hold this alternative conception.

The third example is an example of learners applying the wrong level of generalisation. Students appreciate some key aspects of what isomers are, but restrict the application of the idea to within a single class of compounds. This is not a difficult conception for teachers to tackle, as long as they are able to diagnose it.

The fourth alternative conception in the list refers to an error in categorisation, with the term 'hydrogen bond' taken to mean a covalent bond to hydrogen, rather than a type of intermolecular bond. It seems this idea sometimes arises because students meet hydrogen bonds in biology in the context of nucleic acids and proteins, before they have studied this type of bonding in chemistry (see Chapters 7 and 10). If some teachers simply label a bond as a hydrogen bond without being clear what this means, it is not surprising that students' attempts to make sense of the information in terms of their existing knowledge may lead them to assuming the bond is covalent.

Students commencing post-16 science courses often only have any detailed knowledge of two types of chemical bond – ionic and covalent – so in the absence of any charges being shown, any bond drawn as a line is likely to be identified as a covalent bond.

Now this explanation may seem to suggest that some biology teachers are being careless in not making it clear that a hydrogen bond is a particular type of bond. Yet the research evidence suggests that many post-16 students have great difficulty in learning about new types of bonding. Although classing a hydrogen bond as a covalent bond can be considered as an alternative conception, it may also be part of a more complex alternative framework – the octet framework – for thinking about chemical bonding, that has been found to be quite common by the time a student leaves school.

RS•C

An example of an alternative framework

The octet framework describes the way many students make sense of school ideas about a number of aspects of chemistry (see Figure 1.1).[38, 39] For those who go on to study the subject at post-16 level, these ideas then influence how they make sense of the chemistry they are taught. Although no two students have exactly the same set of ideas, the octet framework describes aspects of student thinking that have been found to be very common. (If you are teaching post-16 chemistry you will probably find most of your students share at least some aspects of this way of thinking.)

Without describing all the evidence for this framework in detail, the following overview shows how this is not just a set of unrelated alternative conceptions. Some aspects of the framework are quite close to scientific thinking, and others may appear quite bizarre – but it is the way these ideas can be integrated into a coherent scheme that is so significant (see Chapter 10).

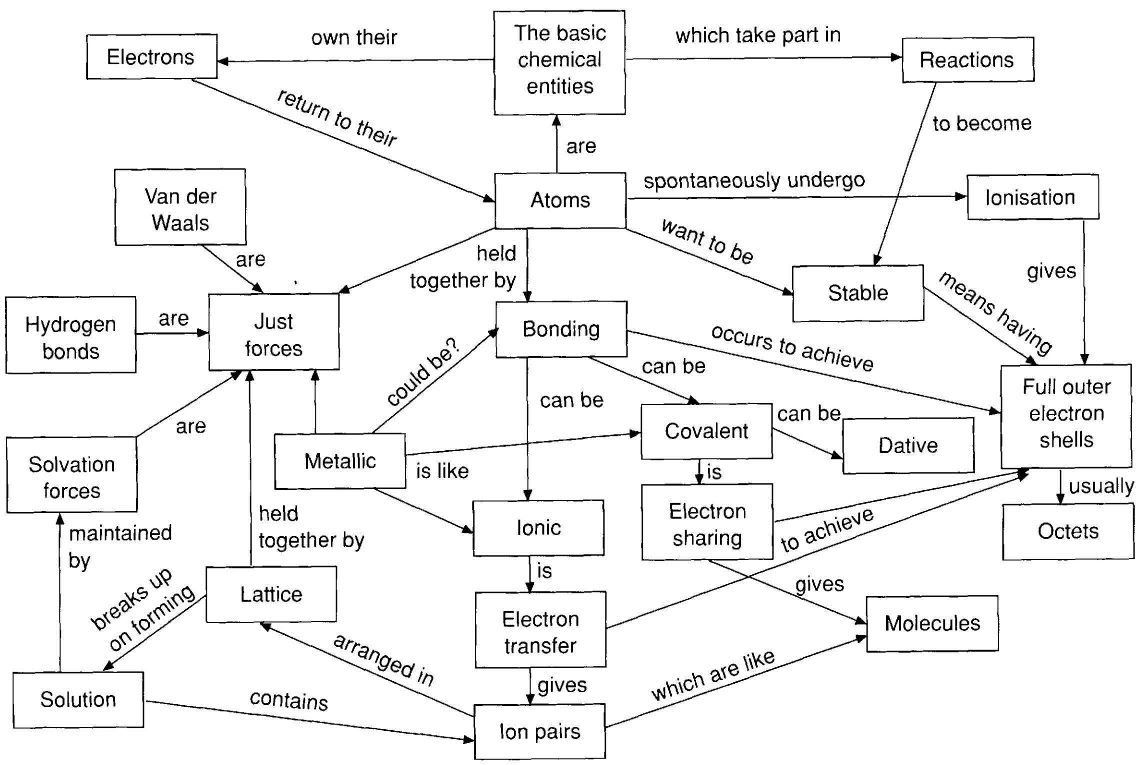

Figure 1.1 An alternative conceptual framework[40]

This framework appears to develop from learners' attempts to understand why bonds form, and why reactions occur. According to this alternative framework:

- reactions occur between atoms (not ions, molecules, lattices etc);
- the reactions occur, and bonds form, so that atoms can obtain full outer shells (or octets) of electrons; and
- there are two ways that atoms can obtain full shells: by electron transfer (ionic bond) or electron sharing (covalent bonding).

Students often take the idea that 'everything is made of atoms' too seriously (see Chapter 6). For one thing they take the meaning that everything is made from atoms to mean that the reactants in chemical reactions always start off as atoms. So they think that sodium chloride is made from atoms

RS•C

of sodium which donate electrons to atoms of chlorine - even though this is not a very likely process chemically! As the ionic bond is identified with the process of electron transfer, each ion is only considered to be fully bonded to one counter ion (see Chapter 8).

Atoms are considered to maintain their discrete identity within molecules, so that bonding electrons are still considered to belong to (and be part of) the atom from which they originated. Students therefore expect atoms to reclaim 'their own' electrons when the bond breaks (making it difficult for students to appreciate heterolytic bond fission). Some students even think that ions must be discharged by electrons returning to 'their own' atoms before new ionic compounds can be precipitated (see Chapter 9).

Because students usually fail to appreciate the physical (that is, electrical) basis of bonding they explain chemical change in anthropomorphic terms: that atoms 'want' or 'need' to have full shells (see Chapter 6). Of course there are very few chemical processes where reactants consist of atoms with partially filled electron shells - so this only makes sense because students tend to think of chemical processes as starting with atoms (see Chapter 9).

As bonding is understood in terms of the need to obtain octets or full shells, students find difficulty in making sense of bonding that can not clearly be seen in these terms. Students will have learnt two mechanisms by which they think full shells can be achieved (electron transfer and electron sharing). So metallic bonding is often seen (initially) as being like ionic and/or covalent bonds. Polar bonding is usually seen as a type of covalent bond (rather than being something intermediate between covalent and ionic). As we saw above, hydrogen bonding may be simply assumed to be a type of covalent bond. When it becomes clear to the student that this is not what is meant, it is then likely to be dismissed as 'just' a force, and not a real chemical bond (see Chapter 8).

Students will have learnt about the stability of electronic structures isoelectronic with the noble gases in their school science. Unfortunately they often generalise this idea beyond the point at which it is scientifically appropriate. Many students at this level consider an isolated sodium cation to be more stable than the isolated atom, and assume than the atom will spontaneously emit an electron, but that the positive cation could not spontaneously attract a negative electron. Some students (even after having studied patterns in successive ionisation energies) will claim that only one electron can be removed from the sodium atom - as it then has an octet.

Any reader who doubts how common these ideas are might try some of the relevant diagnostic probes included in this resource. Would you expect your students to tell you that a highly charged anion of a metallic element (Na^{7-}) is more stable than the neutral atom? The evidence from published research, and the experiences of teachers trying out these resources for the RSC, suggest that many of your students will argue that the sodium anion is more stable as it has a full [*sic*] outer shell of electrons! (See Chapter 6).

Hopefully, reading through this section has persuaded you that students' alternative conceptions in chemistry should be taken seriously. This publication has been designed to help you tackle this issue in the classroom. In this resource and its companion volume you will find:

- information about some of the key alternative conceptions that have been uncovered by research;
- copies of probes you can use to identify these ideas among your own students;
- some specific exercises aimed at challenging some of these alternative ideas;
- ideas about teaching approaches that may help avoid students acquiring some common alternative conceptions;
- general ideas about helping your students develop appropriate scientific conceptions; and
- examples of classroom activities that will help students construct the chemical concepts required in the curriculum.

RS•C

Notes and references for Chapter 1

1. D. Edwards & N. Mercer, *Common Knowledge: The Development of Understanding in the Classroom*, London: Routledge, 1987.
2. K. S. Taber & M. Watts, Learners' explanations for chemical phenomena, *Chemical Education: Research and Practice in Europe*, 2000, **1** (3), 329–353, available at **http://www.uoi.gr/conf_sem/cerapie/** (accessed October 2001).
3. J. Piaget, *The Child's Conception of The World*, St. Albans, UK: Granada, 1973.
4. Many useful references to the literature are given in the review article: K. S. Taber, Chemistry lessons for universities?: a review of constructivist ideas, *University Chemistry Education*, 2000, **4** (2), 26–35.
5. Although learners' ideas in science have attracted considerable attention, alternative conceptions have also been found in other areas of the curriculum. See D. P. Newton, *Teaching for Understanding*, London: RoutledgeFalmer, 2000.
6. R. Driver, *The Pupil as Scientist?* Milton Keynes: Open University Press, 1983.
7. For example: R. Driver, J. Leach, R. Millar & P. Scott, *Young People's Images of Science*, Buckingham: Open University Press, 1996.
8. H. Dickson, *Fantastic Optical Illusions and Puzzles*, London: Lagoon Books, 1996.
9. One of the teachers who piloted materials for this project reported that his group of 13–14 year olds 'were reluctant to relinquish their own ideas' when presented with the materials on Elements, compounds and mixtures.
10. 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.
11. J. Kuiper, Student ideas of science concepts: alternative frameworks?, *International Journal of Science Education*, 1994, **16** (3), 279–292.
12. J. K. Gilbert, R. J. Osborne & P. J. Fensham, *Children's Science and its Consequences for Teaching, Science Education*, 1982, **66** (4), 623–633.
13. J. Bliss, I. Morrison & J. Ogborn, A longitudinal study of dynamics concepts, *International Journal of Science Education*, 1988, **10** (1), 99–110.
14. R. Driver, *The Pupil as Scientist?* Milton Keynes: Open University Press, 1983.
15. D. Dumbrill & G. Birley, Secondary school pupils' understandings of some key physics concepts, *Research in Education*, 1987, **37**, 47–59.
16. L. Viennot, Spontaneous reasoning in elementary dynamics, *European Journal of Science Education*, 1979, **1** (2), 205–222.
17. L. Viennot, Analyzing students' reasoning: tendencies in interpretation, *American Journal of Physics*, 1985, **53** (5), 432–436.
18. Qualifications and Curriculum Authority (QCA), *Standards in Key Stage 3 Science (2000)*, London: QCA, 2001, 12.
19. J. Solomon, *Getting to Know about Energy - in School and Society*, London: Falmer Press, 1992.
20. G. Aikenhead, Renegotiating the culture of school science, in R. Millar, J. Leach & J. Osborne, *Improving Science Education: the Contribution of Research*, Buckingham: Open University Press, 2000.
21. P. Georghiades, *Conceptual change learning in primary science: a step forward?*, 1999, available via Education-line, at **http://www.leeds.ac.uk/educol/** (accessed October 2001).

RS•C

22. J. R. Anderson, *Learning and Memory: An Integrated Approach (2nd Edition)*, New York: John Wiley & Sons, 2000.

23. J. R. Anderson, *Cognitive Psychology and its Implications (4th Edition)*, New York: W. H. Freeman & Company, 1995.

24. I. O. Abimbola, The problem of terminology in the study of student conceptions in science, *Science Education*, 1988, **72** (2), 175–184.

25. D. M. Watts & A. Zylbersztajn, A survey of some children's ideas about force, *Physics Education*, 1981, **16** (6), 360–365.

26. J. K. Gilbert & A. Zylbersztajn, A conceptual framework for science education: The case study of force and movement, *European Journal of Science Education*, 1985, **7** (2), 107–120.

27. B. Bell & A. Brook, *Aspects of Secondary Students' Understanding of Plant Nutrition: Full Report*, Leeds: Children's Learning in Science Project, Centre for Studies in Science & Mathematics Education, University of Leeds, 1984.

28. R. Driver, A. Squires, P. Rushworth & V. Wood-Robinson, *Making Sense of Secondary Science: Research into Children's Ideas*, London: Routledge, 1994.

29. K. S. Taber, The sharing-out of nuclear attraction: or I can't think about Physics in Chemistry, *International Journal of Science Education*, 1998, **20** (8), 1001–1014.

30. K. S. Taber, Ideas about ionisation energy: an instrument to diagnose common alternative conceptions, *School Science Review*, 1999, **81** (295), 97–104.

31. K. S. Taber, The sharing-out of nuclear attraction: or I can't think about Physics in Chemistry, *International Journal of Science Education*, 1998, **20** (8), 1001–1014.

32. V. Barker, *Beyond appearances: Students' Misconceptions about Basic Chemical Ideas:* London: Royal Society of Chemistry, 2000, available on LearnNet at **www.chemsoc.org/LearnNet/miscon.htm** (accessed October 2001).

33. H-J. Schmidt, A label as a hidden persuader: chemists' neutralization concept, *International Journal of Science Education*, 1991, **13** (4), 459–471.

34. H-J. Schmidt and T. Baumgärtner, *Senior high school students' concepts of isotopes – a triangulation study*. In press.

35. H-J. Schmidt, Conceptual difficulties with isomerism, *Journal of Research in Science Teaching*, 1992, **29** (9), 995–1003.

36. K. S. Taber, Building the structural concepts of chemistry: some considerations from educational research, *Chemical Education: Research and Practice in Europe*, 2001, **2** (2), 123–158, available at **http://www.uoi.gr/conf_sem/cerapie/** (accessed October 2001).

37. A. Quinn, Conflicts in perception, in J. Sanger, *The Teaching, Handling Information and Learning Project*, Research Report 67, London: The British Library, 1989.

38. K. S. Taber, An alternative conceptual framework from chemistry education, *International Journal of Science Education*, 1998, **20** (5), 597–608.

39. K. S. Taber, Alternative conceptual frameworks in chemistry, *Education in Chemistry*, 1999, **36** (5), 135–137.

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