Reflections on Misconceptions Paper by Vanessa Barker

In this paper, Barker describes 11 problematic areas in students' understanding of chemistry

1 States of matter
2 Students' ideas about the particulate nature of matter
3 Students' ideas about changes of state
4 Students' ideas about the differences between elements, compounds and mixtures
5 Students' ideas about chemical events
6 Students' ideas about specific chemical events
7 Acids, bases and neutralization
8 Students' difficulties with stoichiometry
9 Students' ideas about chemical bonding
10 Students' ideas about thermodynamics
11 Students' ideas about chemical equilibria

Below I have listed some of what I think are key ideas or questions I have about what Barker is telling us. I have inserted comments from time to time; when you roll the cursor over the highlighted text, the comment pops up.

2.5 Particle Model - Implications for teaching

Four points can be made in summary.

First, only a small proportion of students aged 16 are likely to use a developed particle model to explain physical and chemical phenomena. The continuous model of matter is powerful, such that despite teaching most students use only a primitive particle model, retaining aspects of this naive view. For example, some 16-year olds think the space between gas particles is non-existent or filled, or that particles expand when they are heated. Other students who understand that the gas particles are distributed uniformly explain this by suggesting that repulsive forces exist in between them so implying they are static. A small proportion of students do not use taught particle ideas at all, offering only low-level macroscopic responses to questions involving particle behaviour retaining their naive view of matter in a more complete form.

Second, Novick and Nussbaum (1978) concluded that: "The aspects of the particle model least assimilated by pupils in this study are those most in dissonance with their sensory perception of matter" (p 280). The most problematic ideas are those lacking sensory evidence, such as the existence of empty space between particles. Stavy (1990a) and Benson et al (1993) suggest that visual evidence may help to change students' ideas, since only then is the inadequacy of the naive model made apparent.

Third, evidence suggests that some students apply different ideas to the three states of matter without seeing this as contradictory. For example, students may reason that attractive forces are present between gas particles and that these explain why gas particles may clump together, but they do not use this idea about particles in solids. A student may modify this later to explain the uniform distribution of gas particles in terms of repulsive forces. These ideas may contribute to difficulties for students in understanding chemical bonding.

Fourth, in teaching this topic, the new ideas presented are likely to clash with a child's thinking. Once taught, although a child may use particle terms and ideas in a science lesson to explain demonstrated phenomena, these ideas will not be applied automatically to explain the "real world".

3.2 Phase change - evaporation

An electric kettle was boiled in front of respondents so that bubbles could be seen in the boiling water. They were asked "What are the bubbles made of?". The replies included that the bubbles were made of heat, air, oxygen or hydrogen and steam. The question was answered by over 700 students and the same responses were found. Proportionately, these varied from age 12 - 17 as follows:

heat	30% to 10%
air	30% to 20%
oxygen / hydrogen	25% to 40%
steam	15% to 30%

These data show that while the number offering a correct response, steam, does increase between the ages of 12 and 17, most 17 year olds think either that water can be split into its component elements by heating; or that heat is a substance in its own right; or that air is contained in water. Osborne and Cosgrove attribute these to the influence of teaching; by this age students know the formula of water is H_2O, so imagine that water molecules break up on heating.

3.6 Implications for teaching

Several suggestions can be made.

First, there is a need to help children understand the principles of state changes in general, rather than focusing on water as a specific example. This could be done by systematically reinforcing application of the principles to other substances. Temperatures at which state changes occur could be presented along a scale, so children can see the various points at which everyday substances change state. Language needs to be carefully developed here. For example, "freezing" is associated with "cold", meaning what we sense as cold temperatures, rather than a scientific term for changing from liquid to solid. Thus, children may think that "freezing" can only occur in a freezer, not at over 100°C ("hot"), as is the case for most metals. There is a good opportunity here to draw in the other examples which children encounter in pre-16 science, for example, fractional distillation of crude oil and air. Instead, I find these are taught in other contexts, without reference to basic principles.

Second, particle ideas must be reinforced throughout, using visual images and encouraging discussion of what actually happens to the particles at melting and boiling points in both directions. An example of a strategy may be to ask children one of Cosgrove and Osborne's questions, such as what they think is present in the bubbles when water boils. I have tried this with 16-17 year olds. I asked them to write their answers on pieces of paper without reference to anyone else. I collected them in, then sorted the answers. I pointed out that there was more than one suggestion, most stating "hydrogen and oxygen" or "hydrogen", a very few stating "steam" and that these could not all be correct.

Volunteers justified their suggestions. After discussing all the responses, I used molecular models to encourage students to think about the scientifically correct explanation. We then discussed why the “right” answer was the best one. After this, I tried to reinforce these ideas as opportunities arose.

Third, we need to find better ways of presenting reversible changes to children. The most satisfactory experiments seem to involve solids like naphthalene, which genuinely return to the same state after heating. That is, their physical appearance is the same before and after the change in either direction. It is harder to convince children that droplets on a tile above boiling water are “the same stuff” as the material in the beaker, so maybe this should come after an experiment involving melting and freezing a solid substance.

5.1 Chemical change

Students experience difficulty in recognizing when a chemical reaction occurs. Many do not discriminate consistently between a chemical change and a change of state, which chemists call a "physical change". Evidence for this comes from a number of studies. For example, Ahtee and Varjola (1998) explored 13 - 20 year olds’ meanings for a textbook definition of ‘chemical reaction’. Students were also asked to state what kind of things would indicate a chemical reaction had occurred. They found that around one-fifth of the 13 -14 year olds and 17-18 year olds thought dissolving and change of state were chemical reactions. Only 14% of the 137 university students in the study could explain what actually happened in a chemical reaction.

6.2.3 Burning steel wool

Students predicted how the mass of iron wool would change once burnt in oxygen. About 40% of 15-year olds (Driver, 1985) who had studied chemistry for two years thought the mass of iron would increase because of a reaction with oxygen. These students realize the mass of oxygen must be taken into account. A further 6% thought the mass would increase, but explained that this was due to soot from the flame adding to the dish, possibly influenced by the black appearance of the iron wool after heating. Around 40% thought the mass of the iron would decrease. This group included 19% who suggested gas or smoke would be driven off and 10% who thought that the "burning" would leave ash, which would be lighter than the iron. These students do not recognize the role of oxygen in the reaction, and are using the term "burn" in a non-chemical sense, not "reaction with oxygen". Students’ familiarity with ash remaining after burning coal or wood, which is less bulky than the starting material, may contribute to this. About 5% thought the mass of the iron would be unchanged, for example:

> "It would stay the same because the powder is in the wool but heated up so there is really no difference." (Driver et al, 1985, p 160)

This response conserves the amount of starting material, recognizing that the iron present at the beginning would remain at the end, although this student does not see a role for oxygen in the reaction.

6.2.6 Burning fuels

Similar responses were found in explanations about butane burning. These ideas suggest that although students are aware that burning generates heat, they do not know how the heat is produced. Barker (1995) and Barker and Millar (1999) report 250 16-18 year olds' responses to a slightly modified version of Andersson's "petrol" question. They found that only about 14% of 16 year olds beginning post-16 chemistry courses realized the mass of gas increased relative to the petrol. At the age of 18, this figure increased to 40%. The most frequent incorrect answer was the response "what goes in must come out", given by 44% of 16 year olds and 30% of 18 year olds. Small proportions of students at both stages thought that petrol was converted to light, heat or energy; that the gas was lighter than the starting material so the mass would decrease; and that the petrol was used up or burned away.

The petrol question does not mention the involvement of oxygen, leaving students to realize this for themselves. So, as many may not know what occurs in a car engine, the question may invite the responses "what goes in must come out" and "gases are lighter than liquids", as these are the only bases on which responses can be made from the information provided. Nevertheless, the range of responses was comparable to that for the fuel questions described above and there is certainly evidence to suggest that even where the fuel was burned in the students' presence many still did not realize that oxygen was involved. Although the petrol question appears to be problematic, it is still a valid way of probing students' thinking about an everyday event.

7.1 Misconceptions about acids, bases and neutralization

Even if students "know" that acids "contain hydrogen ions", the chemical behaviour of acids proves difficult to explain. In the second part of her question, Barker invited the same respondents to explain how hydrogen gas forms when a piece of magnesium is added to the acid. About 6% at the start and 17% at the end of the study answered the first part with "hydrogen/oxonium ions" then used the term "displacement reaction" in the second, suggesting that they understood a chemically correct meaning for this. "Displacement reaction" was also used by students who gave incorrect responses to the first part. For example, around 8% initially drew hydrogen chloride molecules and used this phrase, a figure which increased to about 12% by the end. Around 12% of 18 year olds gave the correct ions, but thought that chlorine was displaced. Students seemed to view the acid / metal reaction as a means for hydrogen to "swap partners" with magnesium, perceiving a reaction between the magnesium and "chlorine"/chloride part of hydrogen chloride, rather than between the magnesium atoms and hydrogen/hydronium ions. These findings have implications for teaching about electrode potentials as well as further detailed work on acid-base equilibria.

8 Student difficulties with stoichiometry

More recent work by BouJaoude and Barakat (2000) makes three suggestions about teaching the mole. They developed a stoichiometry test and carried out unstructured interviews with forty 16-17 year old students which revealed misunderstandings about molar quantities, limiting reagent, conservation of matter, molar volume of gases at STP and coefficients in a chemical equation. The authors suggest that teachers should help students develop clear relationships between these ideas before numerical problems are presented. They point out that teachers should also analyse students' approaches to problem solving, suggesting that by doing this students will be prevented from continuing to use incorrect strategies. A third suggestion points to use of problems which stimulate thinking, rather than application of an algorithm. In this study, these authors found this helped to build students' problem-solving abilities.

9.2 Ionic bonds

Butts and Smith (1987) report the results of twenty-eight interviews with 17 year old Australian students who had studied chemical bonding. These students were asked to draw and explain the structure of sodium chloride. While most associated the compound with ionic bonding, many did not appreciate that ionic bonds are three-dimensional. Butts and Smith also report that some students consider sodium chloride to be molecular, suggesting that covalent bonds were present between sodium and chlorine, but that ionic bonds between molecules were needed to create the full structure. Taber (1994) suggests that students acquire this idea because they do not "share the framework of electrostatics knowledge" of the teacher, and also because they are taught about the formation of ionic bonds in a way which promotes the molecular model.

9.4 Implications for teaching

Teachers contribute to students' problems with chemical bonding in several significant ways. First, too much credence is given to the "octet rule" to determine formulae and bonding. This contributes significantly to students' problems with ionic bonding, because they use this (or maybe are taught to) as a technique to determine the formulae of all compounds. In teaching ionic bonds, the rule is applied to show that some atoms "can fill their shells" by electron transfer, instead of electron sharing. The implication is that an ionic bond forms between oppositely charged ions combining to make a molecule, such as "NaCl". This formula satisfies the octet rule, and teaching may end there, leaving students with Taber's "molecular framework". The evidence presented above indicates that as a direct result students cannot fully understand how crystalline lattices form, the behaviour of acidic solutions and the influence ionic bonds have on melting point. In addition, my teaching experience reports students' experiencing problems when faced with the fact that inert gas elements can form compounds - this is contrary to "the rule".

9.5 Suggestions for progress

First, I agree with Taber in thinking that bonding should be taught from an electrostatic perspective. Taber's (1997a) description of "curriculum science" permits definition of an electrostatic "framework" which includes all the components chemists may expect from a competent 18 year old student. My suggestion for helping students to acquire this is to teach that all types of bond are essentially identical in that they all involve electrostatic attraction. Variations in bond type arise from different particles being involved. The point is to emphasize the common factors between bonds, rather than try to stress differences such as “sharing” or “transfer”, “attraction”, “bond” or “force”. Taber points to the use of nuclei and electrons as a way forward for introducing this. He states that “in all chemical processes nuclei and electrons retain their integrity” (1997a, p 388). As this is true, there is no reason why this could not take the place of the “octet rule”, allowing students to look for the electrons and nuclei involved in a bond type.

Third, we can try to use active learning strategies to help students develop their thinking. One strategy I have used with year 10 (14 and 15 year old) students to explore their ideas pre-teaching adopts a “questioning about an event” approach. I demonstrated commonplace events, for example, an ice cube melting, dissolving sodium chloride in water and dissolving sugar in water and asked students to use molecular models to explain what they thought happened to the particles. I involved small groups of students at one time, so arguments could develop about different views. Using this approach I could see students wrestling with conflicting ideas, such as that the sodium chloride lattice might break up into molecules with the formula “NaCl” or break up completely; and that water molecules could break up on heating then reform when cooled or remain intact. The technique requires further development, but allowed me to gauge some idea of students’ thinking and permitted judgement of misconceptions which could be discussed further in a teaching sequence.

10 Students’ ideas about thermodynamics

The simplest chemical idea associated with thermodynamics is that energy is released when bonds form and is required to make bonds break. Post-16 students also learn the First Law of Thermodynamics, which states that "The energy of an isolated system is constant" (Atkins, 1986, p 40) and are taught to apply this in calculations of enthalpy changes. Students' ideas about these aspects of chemistry have received relatively little attention from researchers.

Ross (1993) notes that many students think energy is released when chemical bonds break. He believes this misconception is a barrier to learning which begins when students develop a strong association between fuels and energy, learning the phrase "fuels contain energy" by rote. Development of the idea continues when students associate “fuel is an energy store" with chemical bonds. For example, they will learn that each methane molecule involves forming four covalent bonds between carbon and hydrogen. It is easier to imagine that the energy associated with burning methane is generated when these bonds break, rather than is “leftover” when new bonds form.

10.5 Suggestions for progress

We need to improve pre-16 students’ understanding of energy conservation. One possibility is to adapt Boohan and Ogborn’s (1996) work on teaching energy change. They developed a “picture language” representing a wide range of energy changes which can be used to introduce key ideas, including that energy is conserved not destroyed. Adaption of this so students can apply the language in chemical situations would help introduce the ideas, and further work would lead to the introduction of entropy. The principle early on must be to encourage students to think of energy as being available in either "useful" or "non-useful" forms. A fuel-oxygen system would be a useful form of energy, because we can transfer the energy and make it "work" in heating, cooking or providing electricity. The key point to teach is that this energy is transferred into the environment in many small "packets" which spread out. We cannot use these spread out packages, instead the energy is transferred into the environment in a non-useful format. The amount of energy is still the same, but the process has transformed the energy from "useful" to "useless". In teaching energy ideas, we often say "energy is conserved", but never fully explain why. Using a pictorial language together with explanations which actually show what happens to the energy is needed to help students with this.