
Beyond Appearances:
Students' misconceptions about basic chemical ideas

A report prepared for the Royal Society of Chemistry

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Executive summary

The report presents reviews of research on students’ misconceptions in eleven conceptual areas of chemistry. These are: states of matter; particle theory; changes of state; distinguishing between elements, compounds and mixtures; physical and chemical change; open and closed system chemical events; acids, bases and neutralisation; stoichiometry; chemical bonding; thermodynamics and chemical equilibrium.

The research shows that many students aged 11-18 are likely to have misconceptions in these areas. The most significant misconceptions are described and discussed, together with, where possible, indications about the origins of these.

The implications for teaching chemistry are discussed. These point to far-reaching changes being required in our strategies for teaching, particularly pre-16. Suggestions for progress in each area are made, based in some cases on the author’s own experiences of teaching and research.

The discussion makes suggestions for future work. There is a need to review how we teach the basic ideas which comprise our subject, to help students develop the “molecular spectacles” required for further progress. Among the points made is a need to establish an understanding of how teachers teach, in order to share what “works”, and to develop improvements in our practice.

Contents

1 States of matter

1.1 A naive view of matter

"There are more than three kinds of 'stuff'... "

Direct sensory experience leads children to a naive view of matter involving more than three states, which Hayes (1979) suggests is something like this:-

> "There are different kinds of stuff: iron, water, wood, meat, stone, sand etc. And these exist in different kinds of physical state: solid, liquid, powder, paste, jelly, slime; paper-like etc. Each kind of stuff has a usual state: iron, solid, water, liquid, sand is powder, etc., but this can sometimes be changed. For example, many stuffs will melt if you make them hot enough...and others will burn. Any liquid will freeze if you make it cold enough. Any solid can be powdered... There is no obvious standard way of changing a powder to a solid...
>
> Some solids decompose, i.e. change slowly into some other (useless) substance; or mature, i.e. change slowly into some other (useful) substance..." (p 242-70).

Stavy and Stachel (1985) examined the conceptions children aged between 5 and 12 have of `solid' and `liquid' and found evidence to support Hayes' view. Children think of like metals and wood as typical solids. To them, substances which are not hard and rigid cannot be solids, so classifying solids which do not "fit" this image is difficult. These researchers found that 50% of 12 and 13 year olds classify non-rigid solids such as dough, sponge, sand and sugar separately from coins, glass or chalk. They suggest that:-

> "The easier it is to change the shape or the state of the solid, the less likely it is to be included in the group of solids." (p 418)

Water is the standard " liquid" against which other possible liquids are compared. Children find that pourable powders have liquid properties but do not produce a sensation of wetness, so classify these independently. Children think of water as a typical liquid. Stavy and Stachel found that in general children classify new liquids more easily than solids, perhaps because liquids are less varied in their physical characteristics.

Children appear to rely solely on sensory information when reasoning about matter up to the age of around 14 years. Abstract ideas such as ideas about particles are not readily used to answer questions about the properties of matter, so children persist in thinking that substances are continuous. Millar (1989) suggests that children do not need to use particle ideas because their own theory of matter has worked perfectly well for them. This has implications for influencing change in students' ideas.

1.2 Gases

Gases cause special difficulties for children since those commonly experienced, like air, are invisible. Stavy (1988) suggests this invisibility prevents children from forming a concept of gas spontaneously. She finds instruction is needed for children to acquire knowledge about gas properties, whereas her earlier work suggests that children learn intuitively about solids and liquids. Gases are also conspicuously absent from Hayes' characterisation.

Séré (1986) investigated the ideas 11 year olds have about gases prior to teaching. She found that children associate gases with the use and function of objects, like footballs, tyres and suction pads. Expressions like "hot air rises" (but not "cold air sinks") and "air is everywhere" were commonplace. Also, air was frequently described as being alive, for example, "air always wants to expand everywhere". These ideas may arise through experience of draughts and wind as well as using air around the home.

1.3 Naive ideas about the properties of matter

" 'Stuff' can disappear but its taste and smell stay behind..."

Children's ideas about the behaviour of matter were studied by Piaget and Inhelder (1974). They formulated children's naive view of matter as follows:-

> "a. Matter has no permanent aspect. When matter disappears from sight (e.g. when sugar dissolves in water) it ceases to exist.
>
> b. Matter has a materialistic core to which various random properties having independent existence are attached. Matter can "disappear," whereas its properties (such as sweetness) can continue to exist completely independently of it.
>
> c. Weight is not an intrinsic property of matter. The existence of weightless matter can be accepted.
>
> d. Simple physical transformations (such as dissolution) are not grasped as reversible." (quoted in Stavy, 1990a, p 247)

Research evidence supports these statements. For example, Russell et al (1989 and 1990) asked children aged 5 - 11 to explain the decrease in water level in a large tank after sunny weather. About 45% focused on the remaining water, seeing no need to explain where the "missing" water had gone. For these children the matter had simply ceased to exist (statement `a').

Stavy (1990a) studied 9 - 15 year olds' abilities to conserve weight and matter. Her students were shown propanone evaporating in a closed tube. Around 30% of 9 - 10 year olds in her sample thought the propanone disappeared (statement b). She also found that 30% of the 10 - 12 age group (30%) thought the smell of the propanone remained, although the matter vanished.

Prieto et al (1989) reports that 44% of 14 year olds think a solute "disappears" when dissolved, while 23% label the event "it dissolves" with no explanation. A further 40% of this age group in the Stavy (1990a) study thought that propanone became weightless because it had become invisible (statement `c').

By the age of 15, Stavy (1990a) found that 65% view the evaporation of propanone as reversible, with a large jump in proportion from 25 to 60% at age 13 - 14 when formal teaching about particle ideas is received (statement d).

1.4 Implications for teaching

The impact of the " naive view" on teaching about states of matter

The naive views of matter described by Hayes and Piaget and Inhelder point to three key features of children's reasoning about matter important in teaching. These are:-

> (i) children do not reason consistently - they may use sensory reasoning on some occasions and logical reasoning on others;
>
> (ii) sensory experience dominates in cases where the matter is not visible, leading to the fact that
>
> (iii) many students aged 15 and over still use sensory reasoning about matter, despite being well advanced in thinking logically in other areas, such as mathematics.

Evidence supporting these points includes Stavy's study (1990a), which reports that children reason differently when the substance studied remains visible. Propanone evaporates to form an invisible gas, but solid iodine produces a purple vapour which can be seen. As well as the propanone problem, children explained what they thought occurred when solid iodine was placed in a closed tube and heated to produce the purple vapour. This time, 30 - 50% of children across the 9 - 15 year old age range perceived that the weight of the material was unchanged, while 70 - 95% thought the matter itself was conserved. These contrast with the figures reported earlier for the propanone demonstration.

Stavy's work indicates that 30 - 40% of 15 year olds who have received teaching about the particle theory still use naive ideas about matter in solving particle problems. The Children's Learning In Science (CLIS) project (Brook, Briggs and Driver, 1984) found similar results. Children's naive view of matter, acquired through long experience from childhood, is sufficiently strong to be difficult to relinquish and inhibits consistent thinking about matter. So, although children may have the necessary skills to answer correctly questions about matter which require logical or abstract thought, their naive view leads them to incorrect ideas.

The implications of the persistence of a naive view of matter are wide-ranging, as discussion on the learning of the particulate theory of matter will indicate. Suggestions for progress follow at the end of section 2.

2 Students' ideas about the particulate nature of matter

This has been the subject of extensive research[1]. Findings from these studies lead to the view that particle ideas are poorly grasped, as even with prompting around 25% of students of mixed age used only continuous ideas of matter in their answers.

Misconceptions concerning children's ideas about four basic statements of the particulate nature of matter are discussed:-

- all matter is made of discrete particles;
- particles are in constant random motion
- the space between particles is empty;
- ‘bonds’ or forces exist between particles.

2.1 Matter is made of discrete particles

Children’s naive view of matter is based on the "seeing is believing" principle. Particles cannot be “seen”, so they do not need to exist in a functioning model to explain the behaviour of matter. Novick and Nussbaum (1981) describe the basic learning problem as requiring a learner to:-

> "...overcome immediate perceptions which lead him to a continuous, static view of the structure of matter. He must accommodate his previous naive view of the physical world so as to include a new model adopted by scientists. Internalising the model therefore requires overcoming basic cognitive difficulties of both a conceptual and a perceptual nature."
> (p 187)

Evidence indicates that teaching does prompt change in children’s thinking. In their 1978 study, Novick and Nussbaum used interviews to probe the understanding 13 - 14 year olds had about gases after teaching, finding that about 60% consistently used particle ideas. This figure increased to more than 90% at age 18+. CLIS project involving 15 year olds (Brook, Briggs and Driver, 1984) reports that over half the sample used particle ideas consistently in response to a wide range of questions covering all three states of matter. Recent teaching, as in the Novick and Nussbaum study, generated even higher proportions.

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[1] Papers featuring students’ ideas about the particulate theory of matter include: Dow et al (1978), Brook et al (1984), Gabel (1993), Novick and Nussbaum (1978 and 1981), Mitchell and Kellington (1982), Ben-Zvi et al (1986 and 1987), Gabel et al (1987), Holding (1987), Johnson (1998), Meheut and Chomat (1990) Sequeria and Leite (1990), Haidar and Abraham (1991), Johnston and Driver (1991) Pereira and Elisa (1991), Westbrook and Marek (1991), Scott (1992), Benson et al (1993) and Lee et al (1993).

Johnson (1998a) reports results of a longitudinal interview-based study of 11-14 year olds' understanding of particle ideas. He found that over a two year time span most of the thirty-three pupils moved to a particle model for matter which included scientifically accurate aspects.

Students who do not use particle ideas may use the bulk properties of substances instead. For example, the CLIS study (Brook et al 1984), includes this response in answer to a question concerning the change in temperature of a block of ice:-

> "As the temperature rises to -1 ^{o}C the ice will melt causing the block of ice to get smaller" (p 57).

And about car tyre pressure during a journey:-

> "When a car goes on a journey, the tyres start to warm up and this causes pressure". (p 35)

Brook et al call these "low-level macroscopic" answers, given by children who think of matter as continuous. Many children who appreciate that matter is particulate do not relinquish all their naive view, so ascribe bulk properties to particles themselves:-

> "[particles can] change their form [solid to liquid]; explode, burn, expand, change shape and colour, or shrink" (Happs 1980 p 9 - 14).

Similar ideas were found by Griffiths and Preston (1992), whose small-scale study reports that about 50% of 18-year olds think water molecules in steam are larger than those in ice. This type of explanation seems to be an "intermediate" stage between full appreciation of the particulate nature of matter and naive ideas. Although some students may develop a scientific view, many people may not move from this intermediate stage.

2.2 Particles are in constant random motion

Evidence indicates that random particle motion in liquids and gases is difficult to appreciate. For example, Westbrook and Marek (1991) carried out a study involving about 100 undergraduates, none of whom attributed dye diffusion to random motion of particles.

Students aged 16 and above seem to accept that gas particles are uniformly distributed in a vessel (Novick and Nussbaum 1981), but when asked, "Why don't the particles fall to the bottom?", only around half thought that the particles were in constant motion.

2.3 Space between particles is "empty"

Novick and Nussbaum (1978, 1981) investigated this notion in studies involving Israeli 13-14 year olds and 10-20 year old Americans. They showed that the notion that empty space exists between particles causes students considerable difficulties. They found that 25% of the younger group suggested that although the particles were themselves discrete entities, the space between them was either filled, for example, with:-

> "Dust and other particles; other gases such as oxygen and nitrogen; air, dirt, germs; maybe a liquid; unknown vapours.." (Novick and Nussbaum, 1978 p 276)

or was non-existent, for example:-

> "The particles are closely packed - there is no space between them" or "No place is completely empty". (p 276).

About 40% of 16+ year olds responded to the question "What is there between particles?", with "vapour or oxygen", while a further 10 - 15% thought "a pollutant" was present. University science students also use this "space-filling" model (Benson et al 1993), of whom about 33%

> "seriously underestimated the relative amount of space between the gas particles themselves." (p 596).

Students of all ages find space difficult to imagine and intuitively "fill" it with something. Since students depend on visible, sensory information about solids and liquids to develop their naive view of matter, their difficulty accepting a model proposing there is "nothing" in the spaces between particles is unsurprising.

2.4 ‘Bonds’ or ‘forces’ exist between particles

Students seem to use the notion of forces between particles rather than constant motion to explain gas behaviour. Novick and Nussbaum (1978) asked 13 - 14 year olds to draw a picture to represent air in a partially evacuated flask. A significant proportion drew air around the sides of the flask, or in a mass at the bottom. Others, who indicated that air was composed of tiny particles, showed the particles in clumps or occupying only part of the flask. Explanations offered for these pictures included, "They are held in place by attractive forces..." (Novick and Nussbaum, 1978 p 277). Their 1981 study revealed that about 20% of 16+ year olds think "repulsive forces between the particles" prevent particles falling to the bottom of the flask. The attractive and repulsive force ideas imply static particles, confirming that particle movement in a gas is difficult to grasp. The ‘attractive forces’ suggestion supports the "clumped together" model, while the notion of repulsive forces “ explains” the uniform distribution of particles. No evidence exists to indicate whether any individual student changes from one idea to another between the ages of 14 and 16. However, on accepting that particles are uniformly distributed, the attractive forces notion becomes redundant, so a student may use a new explanation, repulsive forces, instead. The ideas are not necessarily exclusive.

Brook, Briggs and Driver (1984) found that a significant proportion of 15 year olds use attractive forces between gas particles to help explain air pressure. Some students suggest the strength of the forces is temperature dependent. Other 15 year olds did not think forces existed between particles in the solid state (p 74). The report does not indicate if these students also think forces exist between gas particles. However, Engel Clough and Driver (1986) and Stavy (1988) among others report that students do not apply ideas consistently to problems, so the same student could imagine forces to be present between gas particles and not between particles of a solid phase substance.

Students thinking about attractive and repulsive forces may find it hard to learn scientifically correct ideas about changes of state and chemical bonding, both of which involve interaction between particles.

2.5 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".

2.6 Suggestions for progress

In the UK, formal teaching about the particle model is first carried out at KS3, for 11-14 year olds. Lessons usually involve demonstrations or whole class practical experiments to “ illustrate” the particle model together with discussion. The effectiveness of these strategies in developing particle ideas appears to be limited, suggesting that reform could be beneficial. My concern is that in general lessons do not engage the children as active learners, but seek to impose a “ scientist’s view” of the world directly on to the children’s naive view. A strategy which may help children develop particle ideas in a more secure way is needed. To help develop this, points drawn from the research reviewed above may be useful:

- use diagnostic questions to encourage children to talk about their ideas
- use children’s’ answers to these questions to prompt teaching, addressing non-particle ideas in a very explicit way
- present new material/ demonstrations or experiments using particle models explicitly, for example with models, pictures of particles
- reinforce new ideas consistently at every opportunity in other science topics.

The first two points equate to a “ cognitive conflict” strategy to encourage children to be open about their ideas and receptive to new ones when faced with situations which their thinking cannot explain. My observations of science lessons suggest that many teachers “ skim” the central concept, assuming children will learn simply because they have presented “ appropriate” material. Children’s actual thinking remains unchallenged, as no incentive to change their ideas is provided.

The second two points suggest a need to reinforce “ new” ideas visually, encouraging children to think in particle terms. Alongside this is the idea of particle size - using images of atoms may help children realise that particles are very small, and that we tend to think of matter as continuous because this is all our eyes can see.

The final point reflects another trend detected from observing science lessons; the tendency to present topics in isolation, rather than as an integrated whole encouraging development of key ideas. For example, a typical scheme of work may feature “ Kinetic particle theory” for several lessons followed some weeks later (after other topics have intervened) by

“ Chemical reactions” . This topic is frequently taught without reference to particle ideas, allowing children to consider chemical reactions in a “ continuous matter” view rather than picking up the particle theory, using it in practice and reinforcing the concepts taught earlier. There is a need to move away from this “ isolation” practice towards “ integration” .

3 Students' ideas about changes of state

We will see in this section that poor understanding of the four basic aspects of particle theory influences students’ thinking about changes of state. Students’ ideas about this have been studied extensively[2].

3.1 The behaviour of gases

As many students aged up to 18 years do not appreciate that particles are moving, unsurprisingly they find it difficult to explain scientifically what happens when a gas is heated or cooled.

What happens when a gas is heated?

Novick and Nussbaum (1981) report that about 40% of 16 year old students think increased particle motion is the main effect of heating a gas. Over 40% of students aged 16 suggest that "particles are forced apart", while another 20% used the notion of repulsive forces. The CLIS study (Brook et al, 1984) reports similar response levels to a question about air pressure in a car tyre. About 12% of 15-year olds use ideas suggesting that increasing forces between particles cause a change in car tyre pressure during a journey. Séré (1982) studied 11 - 13 year olds' ideas about air pressure, noting that children use mechanistic terms like "force" to describe visual effects. Brook et al also found replies using ideas like particles "swelling", or simply occupying more space.

What happens when a gas is cooled?

Decreasing in particle motion on cooling seems to be harder to understand than the notion of increased particle motion on heating. Recall that about 40% of 16+ students thought that increased particle motion was the main effect heat has on gas particles. The converse question yielded correct responses from less than 30% of 16 - 18 year old students and only 20% of university students (Novick and Nussbaum, 1981). This difference could be because fewer practical examples of cooling gases are available to assist understanding. Approximately 50% of students of any age offered descriptive responses to the question on cooling of gases, including ideas about particles being able to ‘shrink’, ‘condense’, ‘sink’ or ‘settle’.

Taken to an extreme, the cooling of a gas leads to liquefaction. Novick and Nussbaum found

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[2] [2] Research featuring students’ ideas about changes of state include: Andersson (1990), Bar and Travis (1991), Driver et al (1985), Driver et al (1994), Garnett et al (1995), Wandersee et al (1994).

that students may represent this pictorially by drawing particles of air accumulating around the sides or at the bottom of the vessel. Approximately 70% of students from age 13 to university level drew this sort of picture, suggesting that misconceptions about liquefaction are widespread. Novick and Nussbaum (1981) state that

> "...many high school students attribute the decrease in volume of a gas on cooling not to decreased particle motion but to increased attractive forces." (p 192)

3.2 Evaporation

...*among young children*

Young children gain experience of evaporation. Russell et al (1989) report that infants notice evaporation has occurred, but focus on the remaining water, saying some has "disappeared". About one-fifth of 7 - 9 year olds acknowledge that water has gone, but think an outside agent, like another person or the Sun is responsible. Children may also think water soaks into the pan when it is boiled in front of them (Beveridge, 1985), or "went into the plate" if just left to evaporate (Cosgrove and Osborne, 1981). Closer to particle ideas, Russell and Watt (1990) note that other children in the primary age range think water transforms into mist, steam or spray (28%) while a further group describe water as changing to an imperceptible form (17%), such as water vapour or a `gas', for example ,

> "I think the water has split up into millions of tiny micro bits and floated up.." (Russell and Watt, 1990 p 33).

Older children produce the same explanations, but in different proportions, for example, about 57% of the 9 - 11 age group use the idea of an outside agent.

These ideas indicate that thinking about evaporation is linked to understanding conservation of matter. In suggesting that an outside agent has removed the water, children seem to conserve the amount of material, but offer a faulty explanation about why the water disappears. They use sensory based reasoning, applying what are to them satisfying explanations for an invisible change.

...and among secondary school students

Stavy (1990b) studied the link between evaporation and conservation of matter in detail among 9-15 year olds who had been taught particle theory. She examined their responses to two tasks (also reported in Stavy 1990a). Her results suggest that 50% of 15 year olds do not conserve the amount of matter in evaporation. Stavy suggests that confusion arises because of teaching about density and weight. Students say "gas weighs less than liquid", so there is less gas present, thus explaining evaporation in terms of weight change (incorrect) rather than density change (correct).

Osborne and Cosgrove (1983; also reported in Cosgrove and Osborne, 1981) studied New Zealand students aged 8 - 17 years. 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.

Johnson (1998b) carried out a longitudinal study of 11-14 year olds using Cosgrove and Osborne’s questions to explore their thinking about changes of state. He considers that encouraging students to understand boiling water as a state change is important in developing their idea of “ gas” as a substance and argues that teaching particle ideas plays a key role in helping 11-14 year olds accept that bubbles in boiling water are water changed to the gas state. In his later paper (1998c), he suggests that the key point is:

> “ ...that pupils needed to develop and understanding of the gas state that could see water both by itself and as a mixture with the air.” (p 708)

Kruger and Summers (1989) used questions similar to those of Cosgrove and Osborne in their work with primary school teachers. They found that these adults did not use particle ideas often, explaining the phenomenon of evaporation in macroscopic terms. This adds to the evidence presented earlier indicating that people do not readily change their naive ideas about particles and matter, retaining child-like perceptions into adulthood.

3.3 Condensation

Osborne and Cosgrove (1983) report children's ideas about condensation. They held a saucer in the steam leaving a boiling kettle and asked "What is this on the saucer?". Many 10 - 13 year olds said the plate had become "sweaty" or simply "wet". Others of the same age and older said, "The steam turns back into water", or "The oxygen and hydrogen recombine to from water." About one quarter of the 13 - 17 year olds interviewed gave a correct response.

Osborne and Cosgrove collected four major explanations about the origin of water condensing on the outside surface of a sealed glass jar containing ice: "water comes through the glass" (age 8 - 15); "coldness comes through the glass" (age 12 - 17); "the cold surface and dry air (oxygen and hydrogen) react to form water" (age 12 - 17); and "water in the air sticks to the glass" (age 14 - 17). The proportion of 16 - 17 year olds thinking that coldness or water came through the glass was very small, although around 30% of this age group used the idea that gases recombine on the surface to give water.

The authors note that correct responses using particle ideas were exceptions, and that

> "...more ideas to do with particles moving and colliding appeared to be understood by older pupils, but sustained probing of these ideas did not produce sound scientific explanations in terms of intermolecular forces or of loss of kinetic energy." (p 830)

The tenacity of misconceptions suggests that even 16-year old students may find it difficult to apply basic particle ideas to practical situations.

3.4 Melting

Cosgrove and Osborne (1983) report three major ideas expressed by 8 - 17 year olds who were shown ice melting on a teaspoon. The response that the ice "just melts and changes into water" was common. 12 - 13 year olds suggested frequently that the ice is "above its melting temperature" while 14 - 17 year olds thought that "The heat makes the particles move further apart". A small number of 14 to 17 year olds used particle ideas.

Brook et al (1984) asked 15 year olds to explain what happens to ice when it is removed from a freezer at -10^{o}C and left to warm to -1^{o}C. About half of the replies used particle ideas but showed misconceptions in their application. Examples of these answers include:-

> "The block of ice cools and the particles are beginning to break away from each (other) to form gases." (p 53)
>
> "The particles start to break away from each other because of the rise in temperature. When they have broken away from each other, they turn from a crystal form to a solution form." (p 53)

The first reply confuses melting with evaporation whilst the second introduces the idea of dissolving.

Other respondents applied macroscopic ideas such as particles expanding and contracting, for example,

> "As the temperature rises, the particles take in the heat and begin to expand." (p 56)

> "When a block of ice is taken out of a freezer the sudden change of temperature reacts on the particles making them decrease in size." (p 57)

Other suggestions included that the particles melted, or died. However, the question asked was not testing ideas about change of state explicitly, since the temperatures used in the question were both below zero centigrade. So, some of the ideas expressed by students may have resulted from confusion about what they were actually being asked, or interpreted the question as though the ice would melt.

3.5 Freezing

Children's ideas about freezing have not been widely investigated. Stavy (1990b) found that some 6 - 14 year olds realise that melting is reversible, but notes that:-

> "It is possible that pupils of these ages do not have a general conception of the reversibility of the melting process but judge each case specifically."
> (p 509)

So, students may think that although water can be frozen and will melt back to water, this will not necessarily apply to other substances. Stavy (1990b) cites how the words "melting" and "freezing" were applied to candle wax and water. Reversibility of the ice - water state change was accepted by almost all respondents, but the notion of the candle wax melting and freezing was understood by 50% of 10 year olds, rising to 100% only at age 16.

3.6 Implications for teaching

The research points to several key ideas about state changes which teaching should address. First, students do not use particle ideas consistently to explain changes, and if these are expressed, they are frequently incorrect. Examples include thinking that particles can expand, contract or break up and are static. Second, students find it hard to appreciate the reversibility of the state changes, thinking of each process as a separate event. Third, although students may be able to give scientifically correct ideas about the behaviour of water, they cannot apply reasoning to other substances. This suggests that rather than having learned and understood state changes in general, they have learned only about the state changes of water. Their learning has not been fundamental in nature, but rather depends on one example.

3.7 Suggestions for progress

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^o 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.

4 Students' ideas about the differences between elements, compounds and mixtures

Differences between elements, compounds and mixtures form the basis for understanding chemical reactions. Two definitions of "element” illustrate that particle ideas are implicit in making the distinction:-

> "A pure substance which cannot be split up into any other pure substance"
> (Freemantle, 1987 p 123)
>
> "An element is a substance that consists of only one kind of atom." (Atkins 1989 p 8)

To understand Freemantle's phrase "cannot be split up", students must appreciate that matter comprises tiny particles which combine together. To understand Atkins’ definition, students must know the meaning of "atom". The topic has received relatively little attention from researchers, although Barker (1995), Briggs and Holding (1986) and Ben-Zvi et al

(1986) have studied students' thinking about these ideas.

4.1 Making the distinctions

Briggs and Holding (1986) explored how 15 year olds apply particle ideas in making the distinctions between elements, compounds and mixtures. They used coloured dots to represent different atoms in diagrams of a mixture of two elements, a compound and an element alone. About 30% of respondents selected all three correctly, but a number of students could not "...discriminate between particulate representations of compounds and elements" (p 43) and so thought the picture of the compound alone, which showed two different coloured dots joined as molecules, represented an element (7%) or a mixture (39%). Briggs and Holding suggest that

> "..about half of the students regarded any diagram that contained different symbols for atoms, whatever their location, as a representation of a mixture." (p 48)

Interviews showed that students seemed to understand the macroscopic nature of an element, but did not use particle ideas, suggesting that, for example, an element was:-

> "...a single substance...?"
>
> ".... a form of chemical..."
>
> "An element is one, just made up of one substance...well if it was copper it would be made up of just copper..." (p 50 - 51).

These responses indicate understanding that all parts are the same and that an element is "pure". Other responses showed considerable confusion about the particles present in an element, for example,

> "An element is a particular kind of chemical...and all molecules er atoms er molecules of the same substance.." (p 50)
>
> "...[an element] it is part of an atom, something that makes up an atom...um they can be joined by many of them an element is just one part of an atom." (p 50)

Ben-Zvi et al (1986) found that nearly half of 15 year olds attributed the bulk physical properties of copper to single atoms of the element itself, thus making each atom a microscopic version of the element. Briggs and Holding (1986) state

> "...the overall reluctance of students to use particulate ideas in talking about elements, compounds and mixtures may [arise from or result in] gaps in students' thinking. If bridges are not continuously made between the macroscopic and particulate levels then students do not readily cross freely from one to another unless strong cues are present." (p 57)

Barker (1995) carried out a longitudinal study of the understanding of a range of basic chemical ideas among 250 16-18 year old students taking the UK post-16 chemistry course called Advanced (A) level. She found that almost all students starting A level courses in chemistry could distinguish correctly between the Briggs and Holding diagrams.

Briggs and Holding (1986) explored the distinctions 15 year olds make between elements, compounds and mixtures by asking them to identify an element from a list of four substances, each described using basic chemical terminology. Only 21% used particle ideas explicitly in making their choice. Other responses included:-

> "I think it is a because elements can not be split into anything except by chromatography..." (p 19)
>
> "...an element can be split into two more substances..." (p 20).

These students seem to recall a confused form of Atkins' definition. Some respondents suggested that an element burns to give off a gas, or "...most elements need oxygen to stay living" (p 21).

In the same study, students were asked to consider if a substance was an element on the basis of specified results of "tests". Some responses incorporated physical characteristics into a definition of "element", for example,

> "...no element can have a melting point above 200 ^{o}C and dissolve in water to give a colourless solution." (p 31)

Other students confused "element" with chemical characteristics or chemical reactions. Barker's study (1995) revealed that around 3% of 16 year olds beginning A level chemistry courses could give general tests to determine if a substance is an " element" or " compound" , a figure which increased to 17% at the end of the course. She reports that about 43% could define " element" and " compound" correctly at the start of an A level course and that this figure remained unchanged at the end.

Gabel and Samuel (1987) note with concern that

> "Even after the study of chemistry students cannot distinguish between some of the fundamental concepts on which all of chemistry is based such as solids, liquids and gases or elements, mixtures and compounds in terms of the particle model." (p 697)

4.2 Implications for teaching

Students who choose to study chemistry post-16 appear to have little difficulty making distinctions between elements, compounds and mixtures when presented with diagrammatic representations of particles. This indicates that the converse may also be true - that “ non-chemist” students may find making these distinctions problematic, so this fundamental aspect of chemistry remains a mystery.

These data have significant implications for teaching. Students’ understanding of the differences between elements, compounds and mixtures in particle terms is poor. It is therefore unsurprising that students find chemistry “ hard” , as they do not understand a basic principle providing a foundation for more detailed study.

I will discuss this further and make suggestions for progress on this topic at the end of the next section.

5 Introducing “chemical reactions”

Allied to the distinction between elements, compounds and mixtures is the understanding of chemical change. For the purposes of this discussion, a chemical change occurs when atoms (or ions) in reactants are rearranged to form new substances. Often, chemical changes are accompanied by alterations in physical appearance and / or colour, the production of a gas, light, heat, or a cooling effect.

5.1 “Chemical reaction”

Students experience difficulty in recognising 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.

Students’ thinking about the characteristic evidence supporting a chemical reaction was probed by Briggs and Holding (1986). They report 15-year olds’ responses to a question about a "chemical" which loses mass, expands in volume and changes colour on heating. Students were asked if they supported the explanation that a chemical change has occurred. About 18% gave responses indicating agreement, for example:-

> "The substance changes in colour, mass and state, so it would appear to be obvious that a chemical change has taken place." (p 63)

About 23% offered other responses including:-

> "..The mass has melted and has fild (sic) the tupe (sic) but the grams have decreased. The substance has melted so the mas (sic) has gone higher."
> (p 63)
>
> "The colour has changed. It has dissolved." (p 64)

These explanations use the terms "melt" and "dissolve", suggesting confusion with state changes.

Schollum (1981a) reports similar confusion of state vs chemical change. He found that around 70% of 14 year olds and over 50% of 16 year olds thought diluting a strong fruit juice drink by adding water was a chemical change. Schollum also found that 48% of 14 year olds and 55% of 16 year olds thought sugar dissolving was a chemical change. In defining the terms "physical change" and "chemical change", three students described a physical change as:-

> "When something changes its form from what it was before."
>
> "One where a reaction doesn't break up the compounds."
>
> "Change of properties...Can be easily reversed back to its original form."
> (p 20)

The same students defined a chemical change as:-

> "... when the molecular form is changed by doing something, e.g. adding or removing water."
>
> "One where the compounds are broken to form new compounds."
>
> "Change to a different form or state. Is not easily reversed." (p 20).

Applying these definitions, the first student would classify dissolving as a chemical change as this involves adding water. The second distinguishes the changes on the basis of whether compounds are broken or not, while the third focuses on changes of "form". All three thought that sugar dissolving in water was a chemical change.

5.2 What is a 'chemical reaction' anyway?

What should be considered a physical or chemical change? Gensler (1970) dismissed students' difficulties as artificial, saying that chemists were at fault. He disagreed that the traditional phase changes of water should be taught as standard "physical" changes " because the water does not change", saying,

> "Through first hand experience, everybody knows that, in fact, ice is not water; to maintain otherwise smacks of double talk." (p 154)

He continues,

> A detailed description of the processes ...is surely best given in terms of changes in intermolecular "chemical" bonding." (p 155).

Dissolving sugar or salt and recrystallising the solid from solution is commonly done at Key Stage 3 (11-14 year old). Gensler suggests this cannot truly be termed a "physical change" because recrystallised solute requires an act of "blind faith" on the part of the learner to believe this is identical to the starting material. The intermolecular bonds in the solute will differ from the original, and the solid may be hydrated. Gensler says that

> "...in a discipline where experiment is paramount, the novice is being asked to distrust and discard his own experimental results and to place his faith in authority." (p 154).

Thus, he suggests that students' confusion stems from sensory information conflicting with what is being taught. Recrystallised sugar, to a student, is not the same as the stuff which was added originally, so by the teacher's own definition, a chemical change must have occurred.

Redefinition of " chemical change" may help. Strong (1970) suggests that a chemical change be defined by these four characteristics:-

> "(1) Identity of product determined by identity of initial materials
> (2) Mixing of initial materials is essential when more than one reagent is involved
> (3) Discontinuity between properties of initial materials and final product
> (4) Invariance of product properties when temperature, pressure and initial composition are varied." (p 689).

These criteria could be related to sensory characteristics which may help students develop an understanding of the actual changes occurring on the microscopic scale.

Gensler surely has a point worth considering. The wisdom of distinguishing between these two types of change for young students with mainly poor particle models of matter who rely heavily on sensory evidence must be questioned. Ahtee and Variola (1998) note that

> " Only after the concept of atom is introduced is the difference between chemical and physical change obvious." (p 314-5)

They suggest that to help students formulate a clear understanding of 'chemical reaction', a range of phenomena should be presented within an approach which stimulates observation, questioning and argument. The authors also suggest that the atomic description should not be " given too soon" (p 315), but rather wait until students perceive a need for a general explanation in terms other than their own.

5.3 What is a “substance”?: understanding chemical terminology

Chemistry in common with all science has a distinctive vocabulary of words which have very specific meanings for a chemist. A major part of teaching and learning chemistry is approaching this language in a way which assists students in development of their understanding of chemical concepts. Evidence suggests that difficulties may arise because teachers are unaware of the meanings and problems beginning chemists have with these terms, contributing to poor learning of the basic concepts they represent.

To assist with this, Loeffler (1989) suggests a strategy for teaching about the terms “ element” , “ compound” and “ mixture” based around students learning differences between the macroscopic and microscopic worlds. He acknowledges it is chemically incorrect to think of particles behaving individually as large pieces of a substance. He therefore avoids using the word "element" in favour of "substance", which could be used in describing macroscopic properties of any chemical normally named as an element, compound or mixture. The word chemical "species" is used to describe the particles present. So, for example, “ water” comprises the species “ water molecules” . The properties of the substance are taught very specifically as bulk properties, without mentioning particles. This would help students learn about the properties alone, without associating these with the particles present.

After encouraging use of separate terms Loeffler suggests gradually integrating them, making names of substances more precise, for example,

> "Na, atomic sodium .. O_2 molecular oxygen ... S, elemental sulphur" (p 929)

Although this is a good idea, as the macro-microscopic distinction is vital to address, it seems problematic to describe sulphur as “ elemental” in contrast to sodium and oxygen which are also both chemical elements. The strategy adds an extra meaning to “ element” beyond the traditional chemists’ view, so may cause confusion later.

Vogelezang (1987) also thinks that the notion of "substance" should be taught before learning about atoms and molecules because this relates more closely to students' own experiences. As students tend to think of matter as continuous, the term "substance" is closer to their notion of "stuff" than are particle-oriented words "atom" and "molecule". Vogelezang acknowledges that students still need to know about atoms and molecules and advocates de Vos’s and Verdonk’s (1985a, b, 1986, 1987a, b) strategy for this (discussed later). Nevertheless, the proposal supports the views of Stavy (1990a, b) and Novick and Nussbaum (1981) who believe that visual images help students
learn the accepted scientific view of matter presented in science lessons.

However, Johnson (1996) points out that “ substance” does not stand alone as a concept, but relates to other ‘component’ ideas such as material/object, purity, and chemical change. He found that 11-14 year olds misapply these component ideas so do not have a chemist’s view of “ substance” . For example, the students in his study did not classify an iron nail and iron wool as “ solid” , because they thought of solids as “ having no holes” or existing in “ lumps” . A chemist focuses on the material, rather than the shape, so regard both forms as “ solid” . Use of “ pure” is also problematic, because in the everyday world this implies “ untampered with” , or “ natural” . Children think of rock salt as “ pure” but extracted salt as “ impure” because it has gone through a chemical process. Similar reasoning is applied to distilled water. These ideas contradict with the chemist’s view that a pure substance comprises one single substance, rather than more than one.

Ahtee and Variola (1998) also found that students of all ages find the term “ substance” problematic. Students interchanged “ substance” with words like “ element” or “ atom” , for example:-

> “ Substances change outer electrons between them...” (17-18 year old).

These findings suggest that although using “ substance” may be good in principle, clear foundations must be laid about chemists’ meanings of this term before it can be used in a strategy for teaching about chemical and physical changes.

5.4 Teaching about chemical reactions

One such strategy to help students learn the basic ideas discussed above has been suggested by de Vos and Verdonk (1985a, b, 1986, 1987a, b). Entitled “ *A New Road to Reactions*” , the technique requires teachers to avoid a traditional approach based on understanding detailed terminology and instead to present chemical events in a way which promotes students to think of explanations for what they see. The strategy merits detailed description.

First, (1985a) students are encouraged to acknowledge that a chemical change (or reaction) involves production of a new substance. Students grind potassium iodide and lead nitrate *separately* using pestles and mortars prior to tipping one solid into the other. Immediately on mixing, the powders produce a bright yellow solid (lead iodide) mixed with a white solid (potassium nitrate). The teacher fakes anger asking, "Who put that yellow solid in the mortar?". This leads to indignation: “ I don’t know, it just appeared” , “ It came from nowhere” , “ It wasn’t me!” The teacher response is “ Well it can’t have just appeared, it must have come from somewhere! Where did it come from?” Eventually, students may say that the white powders are like tiny eggs, that the yellow powder was inside, so mixing them broke the “ eggs” and caused the yellow stuff to appear. Andersson (1990) suggests this arises because:-

> "It seems that most children at the age of 14 still firmly adhere to an unspoken and unconscious idea that each individual substance is conserved, whatever happens to it." (p 4)

Recognition of the yellow stuff as a new substance is the key point - hence they are reminded that if a white substance was made of " tiny eggs" , the yellow stuff would have appeared during the grinding prior to mixing. Students intuitively prefer to think of the two original substances as existing with the yellow stuff, but something stopped them from seeing the yellow material at the start.

With persistent questioning, students admit the substance is new and "just appeared". The event creates cognitive conflict, as the result and questioning challenges students' thinking. de Vos and Verdonk note:-

> "The role of the teacher *is to make it harder not easier* [italics added] for the student to abandon his or her former idea. The new view on substances should be a personal victory of the student and something to be proud of..." (p 239)

The second stage (de Vos and Verdonk, 1985b) involves helping students to extend this thinking to other reactions and begin to develop a particle model for the events they observe. A petri dish containing a thin layer of water is used initially to observe the formation of lead iodide by migration of ions. Small amounts of the lead nitrate and potassium iodide are placed at opposite sides of the dish. After a few moments, a line of crystalline yellow lead iodide appears in the centre of the dish. Students may explain this using the idea that "molecules" of the substances "attract" one another. This is dispelled when students repeat the experiment by adding one reactant to the dish a few minutes before the other, resulting in instant formation of the precipitate. Other combinations of substances including sugar and salt and salt and lead nitrate help students to realise that precipitates do not always form, even though "molecules" of the substances collide with each other.

Thirdly, de Vos and Verdonk (1986) propose experiments which allow students to realise that heat is involved in chemical reactions. Students feel the temperature rise occurring when steel wool is placed in copper sulphate solution. The authors point out:-

> "[Students] are not looking for a general statement [to explain events] and they have no reason to generalise about chemical reactions on the basis of one particular experiment." (p 973)

This is important, because if a teacher gives a general explanation, students may think that all reactions produce heat. Next, students measure the temperature change occurring when small aliquots of sodium hydroxide solution are added to hydrochloric acid. Students are asked to explain where the heat comes from. The answer involves the formation of new chemical bonds.

The fourth step introduces students to the idea that chemical reactions occur because particles in substances are rearranged. At the start, in stage one, the students thought that the white solids remained unchanged, and that the yellow substance already existed. They were conserving the identity of the white substances and did not realise that these changed in the chemical reaction. de Vos and Verdonk (1987a) note:-

> "..most students attribute a particular identity to a molecule and suppose the molecule keeps this identity throughout chemical reactions... According to this view ... a molecule can go through many radical changes and yet retain its identity and belong to the original species." (p 693)

At this stage the students' tendency to conserve identity of substances is dealt with. The key point students need to learn is that although an atom retains its identity during a chemical reaction, a molecule does not. The authors acknowledge that changing students’ thinking is difficult.

Finally, de Vos and Verdonk (1987b) propose using the decomposition of malachite to introduce the idea that a "molecule" of malachite can be "broken" into two other substances. After this, using a copper cycle, they introduce the idea that a chemical element, copper, cannot be decomposed into anything else. Only then is the term "atom" introduced.

This sequence of steps describes a valuable way of providing visual images to help students form an accepted view of chemical changes. Students are assisted at the outset to make the physical/chemical change distinction and thereafter to realise that chemical changes occur on a microscopic scale between atoms.

5.5 Implications for teaching

The present sequence commonly used to teach about basic chemical ideas appears to create confusion for many secondary-age students. Common practice is to develop chemistry in a hierarchical way building from particle theory, through separation of mixtures and the distinction between elements, compounds and mixtures towards chemical reactions and then features like chemical bonding, rates of reaction and so on. The success of this strategy is limited. Research evidence points to two main areas of weakness.

First, the approach does not permit time or space to develop and consolidate children’s learning about one idea before the next is presented. Assumptions are made at each stage that children have learned as the teacher intended. Little time is given to discovering children’s ideas and to addressing these. As a result, children exhibit very muddled thinking as they attempt to assimilate new scientific views about the world into their own structures. We saw this clearly in children’s learning about particles, in which some children may move towards partial acceptance of a scientific view in ascribing bulk properties to microscopically small atoms. Another example is the difficulty outlined by Gensler (1970) of the physical/chemical change distinction. He is right - we do ask students to make a leap of faith in believing that a substance recovered from solution is the same as the starting material. A third is the problem picked up by Johnson (1996), that the extraction of " pure" salt from rock salt is not considered as purification, but producing a chemical product.

Second, considerable evidence indicates that a key issue is the language of chemistry. Chemists' meanings for words " substance" , " element" and " pure" like differ significantly from everyday meanings. Children need to be given opportunities to learn these chemists' meanings rather than to be told the terms alone.

5.6 Suggestions for progress

de Vos and Verdonk's strategy has much to recommend it. I have tested the first three stages with 16 year old students and found they were challenged and provoked to think in precisely the ways the authors suggest. The approach turns the traditional hierarchy upside-down, by presenting students with strong evidence for chemical reactions and then prompting explanations. These allow the teacher to present a chemist's viewpoint first having acknowledged the student's view. This is crucial - there is then a state of " open-play" as the two positions conflict and the teacher has the key role of ensuring the chemist's view secures " victory" . Students may then perceive a " need" for particle ideas to help explain what they see. There is also then an opportunity for teachers to use the " official" chemical labels for substances and events in a way which has meaning, rather than as abstract terms.

Progress could be made by developing this strategy further. A teaching sequence using this basic outline but also building to develop understanding of key words, linking together ideas from previous lessons, perhaps through concept mapping and adding further examples to reinforce ideas would help promote more secure learning of these basic principles of chemistry than has been possible using traditional systems. These ideas are developed further in section 6.4.

6 Students' ideas about specific chemical events

This section is in two parts - " closed system" chemical reactions or events which do not involve atmospheric oxygen, and " open system" reactions.

6.1 Students' ideas about closed system chemical events

6.1.1 Phosphorus and oxygen in a sealed container

This reaction has formed the basis for a question used in major studies exploring students' misconceptions. The question features a piece of phosphorus placed under water in a sealed flask heated by the Sun. Students are told the phosphorus catches fire, producing a white smoke which dissolves in water. They are asked if the mass of the flask and contents together will be the same, greater, or less than the initial value when all changes are complete. Andersson (1984, 1990) and Briggs et al (1986) report that about 30% of 15 year olds give conservation-type answers, suggesting the mass would be unchanged because "the flask is sealed", for example:-

> "Despite a change of form or state, the same weight is present"
> (Driver, 1985, p 165)
>
> "The flask is sealed. Nothing is added or leaves"
> (Andersson, 1984 p 40 - 42).

A further 16% thought the mass would decrease, suggesting that:-

> "Smoke weighs nothing / is light / is lighter than a solid"
>
> "The phosphorus/the smoke dissolves in the water [so becoming lighter]"
>
> "The phosphorus burns up or is destroyed"
>
> "Oxygen is used up when combustion takes place"
> (Andersson, 1984 p 40 - 42).

Only 6% thought the mass would increase, for example, because:-

> "The smoke is heavier than the phosphorus"
>
> "When the smoke dissolves in the water, the weight increases"
> (Andersson, 1984 p 40 - 42).

Thus, about one-third of students aged 15 do not conserve mass in this reaction. Andersson (1984) suggests that:-

> "If a pupil is to be able to decide whether an amount of matter, or more exactly, mass, is conserved or not, s/he must be able to distinguish between what is material and what is not." (p 45)

If students do not focus immediately on the sealed flask, their response depends mainly on their thoughts about the smoke. Students who think smoke is "material" may offer a conservation response, or suggest the smoke is heavier than the phosphorus. Those who associate "smoke" with the term "gas" and do not think that gases are material will give non-conservation responses. Alternatively, students may also think that matter is used up when a reaction occurs, and hence suggest the mass decreases.

Barker (1995) (reported in Barker and Millar, 1999) used a slightly adapted version of the same question in a longitudinal study of 16 year olds beginning UK post-16 chemistry courses. About 75% of the 250 students involved gave the correct answer, while around 6% confused mass and density, reasoning that the mass would decrease because gas / liquid “weighs less than solid”. 11% thought that mass decreased because the phosphorus dissolves or is used up. By the age of 18, about 81% of the same sample gave the correct answer, while only around 3% confused mass and density and 5% thought the mass would decrease.

6.1.2 Precipitation

Mixing two aqueous solutions may produce a precipitate, for example in tests for reducing sugars and sulphate ions. de Vos and Verdonk make use of precipitation reactions in their teaching scheme, but little other work has been done on students’ understanding about this type of reaction. Barker (1995) and Barker and Millar (1999) probed 16-18 year olds’ thinking about the conservation of mass in a precipitation reaction over a two year period. They found that about 44% of 16 year olds conserved the mass, agreeing that the mass of solid precipitate and liquid has the same mass as the two original liquids. By the end 70% gave this response. Some confusion between weight and density was apparent. About 17% of 16 year olds thought the mass would increase because a solid “weighs more than an liquid” a figure which decreased to about 10% by the end of the study. A third finding was that about 14% of beginning students suggested a gas was produced so the mass would decrease, while 7% gave this answer at the end of the course.

Happs (1980) and Schollum (1982) interviewed students aged 10 - 17 about the formation of a precipitate made on mixing lead nitrate and sodium chloride solutions. Students of all ages tended to describe, rather than explain what they thought had happened, for example:-

> "It's gone all murky" (Happs, 1980, p 10)

Others used scientific language, such "solvent", but very few used "precipitate” to describe the white solid. Older students thought the precipitate was a new substance, while the younger ones described the reaction as substances joining together. However, some older students thought no reaction had occurred:-

> "If those two (sodium chloride and lead nitrate) had reacted, it would have gone clear." (Schollum, 1982, p 12)

6.1.3 Dissolving

Piaget and Inhelder (1974) reported that young children think that sugar "disappears" when dissolved in water, and thus do not "conserve" the mass of material. They are content with the notion that the mass of water would not change, because the substance added to it simply no longer exists. A number of workers including Driver (1985) and Cosgrove and Osborne (1981) have explored the prevalence of this and other explanations among older children. Driver in her study (reported in Briggs et al, 1986) found that about two-thirds of 9 -

14 year olds thought the mass of a sugar solution would be less than the mass of the sugar and water. When a similar problem was given to 15 year olds (Andersson, 1984), over half of the sample thought the mass of the solution would be less. Students offered a variety of explanations, including:-

> "When the sugar dissolves into the water the sugar has no mass so it is just like the 1000 g of the water."
>
> "The sugar will decompose and form a liquid with the water and so will weigh less."
> (Andersson, quoted in Driver et al, 1985, p 154 - 155)

These students do not conserve mass, suggesting that their thinking about this process may not have changed from early childhood.

About 30% of the 15 year olds in the Andersson study predicted that the mass would be unchanged. This figure rose to about 50% of the students who had studied chemistry. Responses in this category clearly showed that students knew the sugar would still be present, for example:-

> "Not one of the two substances would have gone anywhere else except in the pan ... even though the sugar cannot be seem it is still present."
> (Andersson, quoted in Driver et al, 1985, p 154).

Although this response does not use particle ideas, the student certainly conserves mass. Others achieved the same result by adopting an algorithmic approach, adding the masses of solute and solvent given in the question.

In the Cosgrove and Osborne study, about one-quarter of respondents used the word "melt" to describe what happened to sugar, for example:-

> "The sugar is dissolving ... the water is sort of melting the sugar crystals"
> (Cosgrove and Osborne, 1981, p 18)

The terms "dissolve" and "melt" seem here to be used synonymously, although its usage decreased with age.

In the Barker (1995) study (reported in Barker and Millar, 1999) 250 students were asked what they thought the mass of a solution of salt (sodium chloride) would be compared to the mass of solute and solvent. About 57% of 16 year olds thought the masses would have the same value. Several significant misconceptions were found, including 16% who thought that a gas would be released when the salt dissolves and 7% who said that mass was lost in dissolving. By the age of 18, the percentage giving the correct answer was 62%; 15% still thought a gas was produced and about 4% thought mass was lost. These data indicate that some students may think dissolving is a chemical reaction, and that release of a gas is a standard characteristic of this. Alternatively, students may have read “ sodium” rather than

“ sodium chloride” , so misinterpreted the chemical event in the question.

6.1.4 Dissolving an effervescent tablet in water

Students’ ideas about the evolution of a gas from dropping an effervescent tablet in water have been investigated. Schollum (1981a and 1982) interviewed 11 - 17 year olds about the events occurring when a vitamin C tablet is dropped in water. Typically, students said the tablet "dissolved", and that a gas, named by most as ‘air’, was produced. A few older students named the gas ‘carbon dioxide’. Students could not describe how the gas was formed. Some indicated the gas existed already, contained inside the tablet, and was released when the tablet was added to the water, for example:-

> "When they made the tablet they put little air bubbles in"
>
> "...it must have been some sort of airlock in it and the air that's in it forces itself out and up to the top" (1981, p 5)

Others suggested the tablet had reacted with the water:-

> "The tablet is reacting with the water, splitting up the hydrogen and the oxygen. That's turning them into their gas forms and the gas comes out the top." (1981, p 5)

No students explained the gas formed by rearrangement of atoms. The compounds in the tablet which react to form the gas were not named, which perhaps created extra difficulties. Many students described the event as a chemical reaction, but their explanations suggest that they did not really know what this meant. They did not understand that rearrangement of atoms to produce a new substance is involved. This supports the finding of Hesse and Anderson (1992), who note that:-

> "... the term "reaction" was regularly found in students' explanations, yet these students demonstrated little understanding that reactions involve the interaction of atoms and molecules. The misconception remained for most students that scientific explanations involved little more than the ability to 'talk fancy'." (p 294)

Students learn a scientific vocabulary, but not the ideas which lie behind the words.

Andersson (op cit) asked 13 - 16 year olds about the reaction occurring when an aspirin tablet is dropped in water. He found that about 25% of all ages reasoned the gas produced had mass. This suggests that although students cannot explain how the gas is formed, some are at least satisfied that gases are material.

Barker (1995) asked 16-18 year old students a similar question. Few students at any stage of the longitudinal study explained that the gas had not existed but formed in a reaction. About 37% at the beginning and end suggested the gas was already present in the tablet and around 10% described the gas as being “ in solid form” . These data support the suggestion above that students may think of gas evolution as a characteristic of chemical reactions, and that the chemist's meaning of this phrase is not well understood.

6.2 Students' ideas about open system chemical events

Open systems usually involve the oxygen part of the atmosphere in "oxidation" or "combustion" of another substance. Students' ideas about these reactions have been probed by a number of workers including Andersson (1984, 1986 and 1990), Schollum (1981a and b, 1982), Brook et al (1984), BouJaoude (1991), Ross (1987 and 1993), Watson et al (1997), Barker (1995) and Barker and Millar (1999).

6.2.1 The origin of rust

Andersson (1984), Driver (1984) and Schollum (1981a) among others report a consistent pattern of responses among 14 -15 year olds about the origin of rust on an iron nail. A selection is given here.

A minority of students attribute the rust to a chemical reaction, not always seen as including oxygen, for example:-

> "Rust is the form of the chemical reaction after the nail has been taken apart by the rain."
>
> "...caused by water and an impurity in the nail reacting" (Schollum, p 13).

These students seem to have learned "reaction" and use it to describe production of rust. Even when oxygen was known to be involved, students did not necessarily associate this with an increase in mass, for example:-

> "The iron had only reacted with the oxygen of the air which does not weigh anything." (quoted in Driver et al, 1985 p 163).

In this case, the student does not think that gases have mass. More commonly, students thought that the mass of a rusty nail would be lighter than the original nail because the rust "eats away" the metal, for example:-

> "As the nail rusts away it will get smaller.."
>
> "Rust rusts away" (Andersson, 1984 p 34)

Brook et al (op cit) found this response among one-third of 15 year olds. It is similar to the low-level macroscopic thinking reported earlier in that life-like properties are ascribed to the rust. About one-third think the mass of the nail would not change, because the rust was simply "part of the nail", for example:-

> "[The rust is] there all the time under the surface of the nail" (Schollum, 1981a, p 13).

Andersson (1990) calls this "modification"; the rust existed before the event, but became visible when the nail was left in water. A different type of modification idea is reported by Brook et al and Andersson (1984) who found that about one-third of 15-year olds thought the nail would be heavier after rusting:-

> "Rust makes the nails heavier"
>
> "Water is added when rust forms"
>
> "Oxygen is added when rust forms"
>
> "Oxygen and water are added when rust forms" (Andersson, 1984 p 34 - 35).

6.2.2 The reaction between copper and oxygen

Andersson (1984, 1986) and Hesse and Anderson (1992) studied students' thinking about the reaction between copper and oxygen. Andersson asked 13 -15 year olds to explain how a dark coating forms on hot copper pipes. About 10% explained that "This is the way all copper pipes change" (1986, p 552), accepting the event as fact, or " it is just like that" . Other suggestions included that water had seeped through the pipes and caused the coating, an explanation which Andersson describes as "displacement"; and that the copper was changed by the heat ("modification"). About 20% of 15-year olds recognised this, explaining, for example, that:-

> "Copper and oxygen have reacted"
>
> "It is oxidation. Air = oxygen reacts with copper, copper oxide is formed and that is the dark coating." (p 556)

In Hesse and Anderson's (1992) case study, one student (no age is indicated) explained that copper and oxygen reacted with "heat as the catalyst" (p 287). So, although some students have well-developed, accepted views of the copper/oxygen reaction, a majority at age 15 do not.

Barker (1995) asked 16 year old students beginning A level chemistry where the " black stuff" came from when powdered copper metal was heated in air, given that a mass increase occurred. 63% said that it came from a reaction with oxygen. A further 12% suggested from a reaction with " gases/air" , while about 10% suggested the black stuff was soot, carbon or carbon dioxide. At 18 years old, 75% of the same students gave the correct answer and about 8% gave the two main misconception-type answers.

6.2.3 Burning steel (or iron) wool

The rate of the reaction between iron and oxygen can be increased by heating the iron in the atmosphere. When external heat is applied, chemists say the iron is being "burned" or "combusted" in oxygen. Students' ideas about this reaction are reported by Driver et al

(1985), Andersson (1986) and Donnelly and Welford (1988).

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 realise 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 recognise 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, recognising 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.

Andersson (1986) reports one other "transmutation" response among 15 year old chemists:-

> "The steel wool that has burnt has turned into carbon. Carbon weighs more."
>
> "It forms carbon after being red-hot, which makes it heavier." (p 555)

In a previous study (Barker, 1990) found that some 11 and 12 year olds used this reasoning in explaining how "the white stuff" from burning magnesium was formed:-

> "[It] is from burnt carbon/is the soot left after burning"
> (p 69).

This response is perhaps based on students' experiences of burning fuels, which are widely known to contain carbon. In the cases of metals burning, students who do not think as chemists use this information, instead suggesting that one substance can change into another.

Students' ideas about iron burning in oxygen are consistent with those about rusting. We see confusion about conservation of mass and the involvement of oxygen. Next, we will examine students' thinking about fuel / oxygen reactions.

6.2.4 Burning a candle

Students' ideas about burning candles explored by various workers (Meheut et al, 1985; BouJaoude, 1991; Schollum, 1981a, b and Watson et al, 1997). reveal similar response patterns. Around 25% of 14 year olds describe a candle burning as a state change. Meheut et al (1985) found that about 25% of 11 and 12 year olds describe the change as "melting". BouJaoude (1991) found 14 year olds who think a candle decreases in size because the wax evaporates, ignoring the role of the flame. As the oxygen is invisible, students' senses suggest that only state changes occur. Some students think the candle flame is caused by the "wick burning", not the wax (BouJaoude, 1991). This may help explain the state change response, because students could reason that heat from the flame (which is the wick burning) causes the candle to melt.

Students' poor particulate models of matter may contribute to the " change of state" model for burning. Schollum (1981b) reports that a significant proportion of students aged 14 upwards do not perceive either the wax or the flame to be particulate. Those who think the flame is composed of particles describe these as

> "burnt little bits...pretty small bacteria...oxygen from the air ...hydrogen particles from the air." (p 12).

Only two students in thirty-six perceived the flame as particles of hydrocarbon. This finding supports the continuous view of matter discussed earlier.

Meheut et al (1985) report ideas about the role of oxygen in burning a candle. Although most 11 - 12 year olds knew oxygen was needed for burning, they could not explain exactly how the oxygen was used. A number thought the oxygen was "used up" or "burnt away". In BouJaoude's study (1991), 14 year olds were interviewed about the involvement of oxygen in a candle burning. One student said:-

> "Oxygen feeds the fire and keeps the candle burning" (p 695).

Thus, the role of oxygen in burning candle wax is not well known. Instead, students may think that a state change is occurring, decreasing the candle mass by evaporation of wax. This thinking conserves the amount of original material. The view that oxygen is "used up" also appears prevalent, indicating that some students think oxygen is destroyed on burning.

Watson et al (1997) describe the explanations given by 150 14 and 15 year olds to questions about aspects of combustion, including ideas about what happens when a candle enclosed in a gas jar burns for a few seconds. In exploring the consistency of explanations across a range of combustion reactions, the authors found three types of framework based on the categories " chemical reaction" , " transmutation" and " modification" in Andersson's (1990) model. They note that students using a transmutation framework including ideas such as material being changed into heat, oxygen " feeding the flame" and non-conservation of mass in a combustion reaction tend to use this thinking consistently across a range of situations. The tenacity of this framework may in part be due to the limitations of student experience, as it “works” well for carbon- and hydrogen-based fuels which are used commonly in pre-16 courses. A second group using modification ideas in which, for example, oxygen is not involved in the change, or the flame is the source of heat for the reaction tend to adapt their thinking according to the characteristics of the substance being burned. A third group use chemical reaction ideas and transmutation ideas. Watson et al suggest that students whose responses are inconsistent may be moving from one “theory” for explaining combustion to another. They indicate several aspects of combustion which are absent from students’ responses, including the formation of imperceptible products such as gases, the weight of gases and the existence of atoms or molecules. Success in making the transition to a “chemical reaction” framework may depend on the extent to which students understand these imperceptible aspects.

6.2.5 Burning butane

BouJaoude (1991) and Schollum (1981a, b) asked students to explain what they thought was happening when a gas burner was lit. Schollum (1981b) reports that students agreed readily that "burning" occurred. Noticeably, students did not use the change of state model, perhaps because gas cannot melt! 12 - 15 year olds suggested frequently that the gas was destroyed, for example:-

> "The gas is eating up, no the flames are eating up the gas... It eats it up and then it goes up in little pieces." (1981b, p 7)

One student in BouJaoude’s study used similar reasoning to explain that oxygen was "burned up".

Schollum reports that many students aged up to 17 years think heat is produced, for example:-

> "It turns into heat or heat waves." (1981b p 7)

Some older students described the products as carbon dioxide and hydrogen, suggesting that the role of oxygen in producing carbon dioxide and water was not well known. Since students may use this reaction everyday in cooking or heating, the “gas becomes heat” response may be expected. However, these responses indicate that a high proportion of 14 - 15 year olds may think that gas or oxygen is destroyed when burning occurs.

6.2.6 Burning petrol

Andersson (1984) reports the ideas 15 year olds have about burning petrol in a car engine. Students were asked to predict the mass of exhaust gas formed when 50 kg of petrol was placed in a car which was then driven until the tank was empty. Their responses can be compared with those given to the conservation of mass in closed systems, reported in section 6.1.

Andersson found that only 3% of 15 year olds thought the mass of the fuel would increase. Although some gave the expected response, that petrol had reacted with oxygen, others thought the mass would increase because:-

> "The petrol is mixed with the air and then it gets heavier." (p 38)

This student recognised that air was involved, but did not appear to think that a chemical reaction had occurred. However, the terms "mixed" and "reacted" may, to these students, be synonymous, so this could be their way of saying that a reaction had occurred.

Over 50% of Andersson's respondents thought the mass of the petrol would be unchanged. Many used the state change model, for example,

> "Even if it doesn't come out in liquid form it must weigh just as much."
> (p 38)

This indirectly says that the petrol turned into gas, mirroring the candle wax "melts" response described above. These students do not perceive that oxygen is involved, but conserve the amount of petrol.

About 27% of respondents thought the mass of exhaust gas would be less than the mass of petrol for at least two reasons. First, gases “ do not weigh as much as liquids” , so independent of what happened to the petrol, that gases are emitted means the mass must be less, for example:-

> "Gas is lighter than petrol (water), so if you only have 50 kg of petrol and it's transformed into gas, it must be lighter..". (p 37)

This response confuses mass and density. They may conserve amount of stuff, but think that the measurable mass has changed.

A second explanation for mass decrease is that petrol has changed (“ transmuted”) into energy, for example:-

> "It's less than 50 kg because part of the petrol was been changed into heat and kinetic energy." (Andersson, 1986 p 555)

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 realised 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 realise 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 realise 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.

6.3 Implications for teaching

Significant implications for teaching can be drawn from these data. The evidence suggests that children may think about chemical reactions using any one of several faulty models. They may apply a “ change of state” model to a reaction involving atmospheric oxygen, and so miss the critical point that new substance(s) are forming. Second, students may “ transmute” chemicals at will, so that magnesium may turn into carbon, or petrol into energy. A third possibility is that students might use a “ modification” model, explaining that the gas produced on dissolving a tablet was already present in a different form, or that the rust produced on a nail came from inside.

There are perhaps two main reasons for the apparent validity of these models. First, is that gases are involved, which earlier discussion indicates are problematic for students. Some find it hard to accept gases as “ substances” , and do not think they have mass, or confuse mass and density. Also, most gases are invisible, so presenting a reaction involving oxygen is difficult to understand because this is removed from the air without anyone being able to see this happening. As we saw above, in discussing the development of particle ideas, students depend quite rightly on their senses so cannot justify the inclusion of an invisible substance. The second reason draws on earlier discussion. Poor particle models of matter contribute to students’ difficulties. Without really understanding what occurs on a molecular level, students generate their own theories naturally. However, this is not intended to justify the present “ particle upwards” system for teaching chemistry. Rather the intention is to indicate that to develop sound understanding, changes in teaching strategy are needed.

6.4 Suggestions for progress

In an earlier section (5. 6) I suggested that de Vos and Verdonk's (1985) strategy for developing understanding of chemical reactions be developed further. The discussion in this section suggests ways of doing this.

First, diagnostic questions such as those used in research studies could be used in consistent ways to investigate children's ideas prior to teaching. Responses must inform teachers about lesson content - there is no point undertaking this kind of activity if the remainder of a lesson is unchanged. Teachers must discuss models for chemical reactions openly, developing an atmosphere in which children can feel comfortable talking about " wrong" ideas while working towards an accepted chemist's view.

To do this several features of a basic chemistry course are essential. First, is a need for consistency in approach. Knowing that many children have poor understanding of particle ideas and so cannot visualise particles reacting suggests that we should develop strategies which reinforce this using models and other visual images. Second, my experience from teaching and observation of lessons suggests that many children experience a very limited range of chemical reactions, selected to perhaps minimise cost, teach a specific point, or to use in an investigation. The sequence they experience passes so quickly that it is impossible for them to consolidate any ideas, so unsurprisingly assemble non-chemical models to explain events. There is a need to extend the range of reactions children experience, for example by allowing them to see several fuel-oxygen systems, encouraging discussion about their models on seeing the first one but moving towards a chemically correct position by the last. This, with strategies suggested above, could help remove the dependence on " change of state" and other models, developing a more reliable and consistent understanding of the reaction.

7 Students' thinking about acids, bases and neutralisation

7.1 Misconceptions about acids, bases and neutralisation

Workers including Hand and Treagust (1988), Nakhleh (1992), Ross and Munby (1991) and Cros et al (1986, 1988) have studied students' ideas about the nature of acids, bases and neutralisation. The studies reveal some consistency with earlier discussion about students' models for chemical reactions.

Hand and Treagust (1988) identified five key misconceptions about acids and bases among sixty 16 year old students. These were :-

> "(1) An acid is something which eats material away or which can burn you;
> (2) Testing for acids can only be done by trying to eat something away;
> (3) Neutralisation is the breakdown of an acid or something changing from an acid;

(4) The difference between a strong and a weak acid is that strong acids eat material away faster than a weak acid; and
(5) A base is something which makes up an acid." (p 55)

No particle ideas are used here: the students give descriptive statements emphasising a continuous, non-particulate model for acids and bases, some including active, anthropomorphic ideas such as “eating away”. This non-particulate view persists for a minority of students, as Nakhleh (1992) found. 20% of 17 year old chemists in her study drew images consistent with a non-particulate model of an acid when asked how an acid or base would "appear under a very powerful magnifying glass" (p 192). This implies that although students may measure pH and know about the corrosive qualities of acids and bases, some find it hard to associate properties with the particles present.

In Barker’s longitudinal study (1995), participants were asked a two-part question involving hydrochloric acid. In the first part, students were invited to draw a diagram showing how hydrochloric acid forms from hydrogen chloride gas and water. About half of the respondents gave particle-based answers, with about 12% of 16 year olds drawing hydrogen or oxonium ions and 40% hydrogen chloride molecules. At the end of the study, almost 80% used particle ideas, divided between 37% drawing hydrogen/oxonium ions and 40% hydrogen chloride molecules. This supports Ross and Munby's (1991) interviews with 17 year old students which showed that the notion of an "acid containing hydrogen ions" was reasonably well-known.

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/oxonium ions. These findings have implications for teaching about electrode potentials as well as further detailed work on acid-base equilibria.

Some evidence supports the view that definitions of “acid” and “base” together with changing these also causes difficulties for students. Hand (1989) followed up twenty-four of the students reported in Hand and Treagust (1988). At this later stage, some students had been taught much more sophisticated ideas in a pure chemistry course, while others had studied a broader based science course or biology. A test based on the five original misconceptions was administered to the group. The results indicated that only students studying chemistry could answer basic recall questions correctly, while those studying biology did best overall. The author concluded that the biologists did better because "they were not having any interference from new definitions" (p 142). Carr (1984) agrees with this, stating that students' difficulties with acids and bases are:-

> "more usefully perceived in terms of confusion about the models used in teaching the concept rather than as a conflict between preconceptions and the scientific view" (p 97).

In advanced chemistry courses, acids and bases are redefined under the Brönsted-Lowry theory as "donors" and "acceptors", moving away from the Arrhenius definitions of an acid being a "substance which yields hydrogen ions" and a base producing hydroxide ions in solution. Hand suggests that presenting students with this new theory confuses them. Hawkes (1992) supports this, stating:-

> "It is inherent in human nature that we accept what we are told first and relinquish or change it with difficulty." (p 543)

Students studying chemistry post-16 may continue to use ideas learned much earlier and see no reason to change them.

Cros et al (1986, 1988) investigated French university science students' ideas about acids and bases, finding that the concept of bases was far less developed than that of acids. Many students gave the Arrhenius definition of bases being OH^- donors. Students could not name bases as easily as acids, giving only ammonia and sodium or potassium hydroxide as responses. Second year students showed no improvement on the first years in these respects.

7.2 Implications for teaching

Acid / base reactions feature in most pre-16 chemistry courses. Teachers must therefore be aware of students’ difficulties with these reactions. Students’ problems may arise because acids and alkalis both look like water. Reacting them together needs precision and some way of knowing that neutralisation is complete, so an indicator is required. Addition of this extra chemical adds and extra layer of “ mystery” . A common experiment too at this level is to investigate the acid/ base nature of everyday substances using universal indicator. Thus, students find out that toothpaste, baking powder, soap, bleach, vinegar, tomato sauce and other well-known household items have a specific chemical property which we “ label” as acid or base.

The research evidence points to students developing ideas about acids much more readily than bases. Hand and Treagust's misconceptions almost all relate to acids specifically. Anecdotal evidence from my own experience supports this; students think of an alkali/base as a substance which inhibits the burning qualities of an acid, rather than having corrosive properties of its own. Teachers must develop stronger awareness of the properties of bases.

The behaviour of acids also suggests implications for teaching. Pre-16 courses also feature displacement and metal/ acid reactions. Evidence presented here suggests that students apply a model for these reactions based on hydrogen ions " swapping partners" , and so make errors in predicting products of these exchanges.

7.3 Suggestions for progress

de Vos and Verdonk's strategy includes introducing students to an acid/ base reaction with the specific aim of showing that this generates heat energy. This could be extended to help students realise that these two substances have distinctive chemical properties. Again, a consistent approach must be used to help students realise the common products. Also, they must be introduced to the properties of acids and bases explicitly, to help address the perception that acids are " bad" and bases " good" .

8 Students' difficulties with stoichiometry

Moles link the substances represented in a chemical equation to the amounts needed in practice. Moles are an abstract idea - we cannot " see" Avogadro's number of particles, so the best we can do is to present an idea of how big this is. To use the mole meaningfully requires mathematical skills, which present an additional challenge.

8.1.1 One cause of the difficulties: defining "the mole"

Students difficulties with "the mole concept" have been known for a long period (Lazonby et al 1982). Given that particle ideas are often poor or inconsistent among teenage chemists, difficulties are unsurprising. Dierks (1981) notes that the mole has only been adopted as a unit in chemistry in relatively recent years. He says that discussion of "the mole problem" began in 1953 (p 146) and that thereafter chemists spent a number of years agreeing on a definition. The word "mole" acquired three meanings: an individual unit of mass; a portion of substance; and a number (p 150). Chemistry teachers frequently adopt the simplistic standpoint of the mole as a " counting unit" . Nelson (1991) disagrees with this approach on the grounds that in fact the mole is not strictly defined as a number, but rather as:

> " ...the amount of substance corresponding to the number of atoms in 0.012 kg of carbon-12." (p 103).

Dierks suggests that problems also arise when moles are introduced to students who are not being prepared to become professional chemists. He reports that early work on students' difficulties centred on the vital connection between chemical formulae / equations and mathematical expressions representing amounts of substance. He states:-

> "It is generally argued .. that pupils need a clear conception of what is meant by amount of substance if they are to work successfully with this concept. This concept can apparently only be developed when amount of substance is interpreted as a numerical quantity." (p 152)

Adopting the Ausubelian argument that "meaningful learning occurs when new information is linked with existing concepts" (p 153), Dierks advocates beginning to teach the mole as a "number". This contrasts directly with Nelson (1991) who suggests strongly that the mole should be taught as an “ amount” , suggesting use of the term “ chemical amount” rather than “ amount of substance” . This difference may be at the centre of problems associated with the mole - in teaching this concept, we may use “ amount of substance” and “ number of particles” synonymously, contributing unwittingly to students’ difficulties by never really explaining what we mean in either case.

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.

8.1.2 Students’ mathematical skills

As BouJaoude and Barakat implied above, students' mathematical expertise also contributes to their difficulties. A student who cannot manipulate numbers readily is unlikely to be successful in learning about moles. Shayer (1970, cited in Rowell and Dawson, 1980) explains students' difficulties in terms of their lack of the cognitive skills "necessary to deal with the concept" (p 693). Shayer believes that students who have not reached Piaget's formal operational stage of thinking cannot learn about moles, because cognitive skills such as proportional and ratio reasoning are undeveloped. This is in broad agreement with Dierks' suggestion, since formal operational thinking involves:-

> "the ability to ... see the need to control variables in making inferences from data and to impose quantitative models on observations, specifically that of

> proportionality." (Driver, 1983 p 61)

Rowell and Dawson and Nelson (1991) dispute this, suggesting that students require an appropriate step-wise scheme leading towards using moles in an accepted way.

8.2 Students' thinking about reacting mass reasoning

Barker (1995) reports the responses of 250 16-17 year olds to a question about the reaction between iron and sulphur, adapted from Briggs and Holding (1986). They were told that 56 g of iron reacts with 32 g sulphur to give 88 g iron sulphide and were asked to predict what would be produced when 112 g iron and 80 g sulphur react. At the start of the two-year study, about 50% gave the correct answer, that 176 g iron sulphide would be produced with some sulphur remaining. The most common incorrect response, given by 32%, was to add the two figures generating 192 g. These students had not realised the need to apply reacting mass reasoning. At the end of their two year course of study, about 72% gave the correct answer, while about 16% gave 192 g.

BouJaoude and Barakat (2000) report that about 40% of their sample of forty 16-17 year olds calculated molar mass by dividing or mulitplying the total of atomic masses by the coefficient shown in the chemical equation.

8.3 Learning about moles

Modelling a chemical reaction

Rowell and Dawson (1980) begin teaching moles to 16 year old students by using a model of a simple chemical reaction such as $2Na + S \rightarrow Na_2S$ represented in small coins. Next, the idea of proportionality is introduced by showing a reaction in which " 2As" make " 1C" . Students are asked what would be produced if only " 1A" was available. Once the idea that reactions occur in proportion was developed, Rowell and Dawson introduce the idea that the number of particles involved might be very large. At this point, they return to their original reaction and ask students to imagine that these are atoms of chemical elements. The conservation of number of atoms and masses are emphasised at each point. The authors carried out a six-week teaching strategy using this stepwise approach and tested students before, immediately afterwards and two months later. They found that twenty-one out of the twenty-four students gave error-free responses in the final test. This refutes the Shayer suggestion, since the students were not pre-selected for their ability to think in a formal operational way. The authors conclude:-

> "Teaching the mole concept is not an easy task but it need not be the mountain that some have made it." (p 707)

Using algorithms

Kean et al (1988) advocate algorithms to help teach and learn mole ideas. They note that a useful algorithm "allows students to solve problems with meaning rather than by rote" (p 987). They suggest an eight-step strategy to help students devise an algorithm for converting mass into volume measurements and vice versa. Similarly, students can be taught an algorithm for solving proportionality problems and, eventually, calculation of reacting masses. This strategy may help develop students' confidence in handling numerical data, but requires careful instruction to ensure appropriate application. Finley et al (1992) sound a warning note:-

> "Recent research has indicated that the ability to solve numerical problems does not guarantee conceptual understanding of the molecular basis of the problem." (p 254)

Although Kean et al's proposals may provide a means to an end, the students may learn the algorithm and not its chemical meaning. Rowell and Dawson’s approach, rooted firmly in the chemical principles of stoichiometry, has much to recommend it.

8.4 Implications for teaching

These data suggest that there is little agreement on a strategy for teaching the mole successfully, that is, to ensure students understand the principle. In fact, evidence points to fundamental disagreement about presenting the “ mole” as an amount or a number. These differences may well result in adoption of teaching strategies according to an individual standpoint, rather than considering the students’ needs. Researchers also point to students experiencing problems in applying mole ideas to other areas of chemistry, usually because mathematical skills are poor. A third difficulty is the tendency to promote use of algorithms in teaching the mole, rather than to develop understanding.

All these may result in a wide variety of understandings and difficulties about the mole among students. Understanding the mole is central to making progress in chemistry beyond the basic level, so it is extremely important that teachers get this right. Suggestions for progress follow.

8.5 Suggestions for progress

There is a strong perception that “ the mole” is a “ difficult” topic which can only be taught to the most able students. I find this hard to justify. With care, an understanding of the mole as a number and as a way of representing an amount of substance, can be achieved by a majority of pre-16 students. At issue is the approach to be taken.

I advocate presenting the mole initially as a convenient way to count large numbers of atoms. The unit defined by Avogadro’s number of particles represents a convenient amount of substance which can be measured using conventional equipment. The number of moles can be manipulated by simple mathematical techniques to give concentrations and then, for example, pH values. however, the key idea is for students to realise that the M_r or A_r value of any substance measured as a mass in grams all contain the same number of particles. Once this is understood, “ moles” can be manipulated mathematically using the simple relationship moles = mass / M_r or A_r. It is a relatively short step from this to working with concentrations of moles in solution.

When I began teaching chemistry, several experienced teachers suggested ways I could present the mole to students for the first time. In case any reader needs one, I will describe the method I have found most successful.

The starting point is two samples of chemical elements with A_r values which are in a whole number ratio. A good example is copper (allow A_r = 64) and sulphur (A_r =32), although other pairs are possible. I begin by showing students measured out samples, labelled very clearly " 64 g copper" and " 32 g sulphur" and asking them to note the ratio. I also get them to look at the relative amounts by appearance in the jars. With some groups I would not use the term " ratio" but say " how many times does the mass of sulphur go into the mass of copper?" . Students always get this right. I then start to make a list - one for copper, the other for sulphur, beginning by writing the symbols on a board. Under these follow " 64 g" and " 32 g" and then " 2 : 1" . Then I ask students to imagine I have one atom each of copper and sulphur. I ask them to tell me the ratio of mass of the atoms. I write 1 atom under each heading. I ask if we can physically measure out 1 atom of each for experiments. The reply is no, because the atoms are too small to be measured on a balance in our laboratory. Then I ask the same question about increasing numbers of atoms, 100, 1000, 1 million and estimate the mass - very small; in each case we could not measure out an amount we could use, but each time the ratio of mass is the same. This is important. Then I switch the question and say, " Now, look at the samples again. They are in the same ratio. We can measure these amounts. What can you say about the number of atoms in these samples?" Usually a class needs a few seconds to think about this. I have found it best not to interrupt this thinking. Then one person invariably gives the response, " They must contain the same number of atoms" . This response requires enormous praise, as the student has made quite a leap in working this key point out. As soon as one person has got this, there is a domino effect. Sometimes the procedure has to be repeated. Once satisfied that the message has got home, I discuss what the number is, showing an indication of the size and reinforcing the idea that atoms are very small. The points to emphasise are that the mass weighed in grams of anything contains Avogadro's number and that all the masses exist in fixed ratios to each other which cannot be changed. Following this, students can be given material to work on to reinforce and support these ideas.

I consider that the advantage of an approach like this is that it does not overcomplicate the issue, but provides a clear thinking strategy which is within reach of most students. Once the introductory session is complete, regular reinforcement is needed. This leads to the second suggestion for progress - that of ensuring students have confidence in their mathematical ability. I am aware that many schools and colleges use or are developing maths courses specifically for chemists, and would strongly encourage this. Students need to feel confident in using mathematics principles as tools for developing understanding within chemistry, rather than high hurdles to be crossed and usually knocked over.

Above all, the mole is a topic which requires patience and care in its introduction, reinforcement afterwards, and continued praise for students who struggle with maths and in making sense of this abstract idea.

9 Students' ideas about chemical bonding

Chemists have studied extensively the ways in which particles combine to make the seemingly infinite range of substances at our disposal. Almost all molecules have bonds which fall between the two extremes of "covalent" and “ionic” bonding. The behaviour of a substance is influenced by intermolecular bonds, which, if extensive, influence boiling and melting points, structure and potential use. Students are introduced to intermolecular bonds during post-16 chemistry courses. Relatively little work has been carried out on students' ideas about chemical bonding prior to the age of 16.

9.1 Covalent bonds

The simplest idea associated with the formation of a single covalent bond is that a pair of electrons is shared between two atoms, and for a double bond two electron pairs are shared. In either case the sharing confers additional stability on both atoms involved and a fixed amount of energy is required to break the bond.

The development of basic ideas

Barker (1994) reports the changes in students’ basic ideas about covalent bonds and molecular structure over a two-year period. About 18% of 16 year olds could distinguish between single and double covalent bonds in methane, ethene and water molecules in terms of the numbers of electrons involved. About 66% of the student population could do this about fifteen months later. A further 25% at this stage distinguished between single and double bonds, but did not specify the numbers of electrons involved. About 7% of students at the end of the study thought the bonds had 1 or 2 electrons.

In a companion question, Barker explored students’ ideas about the energetics involved in bond formation by asking students why a methane molecule has the formula CH_4. Very few students at any point in the survey responded in energetics terms, but about 6% at the start and 16% at the end said that “C and H are more stable as CH_4.” A very popular response, given by 56% of 16 year olds and 61% of 18 year olds was “C needs four bonds”. This answer ignores the hydrogen in the molecule and attributes anthropomorphic behaviour to the carbon atom. This kind of language was found by Taber and Watts (1996) to be extensive and not only used by students but also by teachers in their drive to promote understanding of science issues.

Progression in understanding

Taber (1997a) carried out case studies exploring A level chemistry students' developing understanding of chemical bonding. An early report (Taber 1993a and b) describes "Annie's" three interviews about chemical bonding and indicates progression in her understanding. In the first interview, she recognised that a covalent bond exists in diatomic molecules in which the two atoms are identical. She did not explain covalent bond formation in terms of sharing electrons. Instead, Annie said that the atoms "pull together". To decide if a bond was covalent Annie looked at the chemical elements involved to establish if both were non-metals. If this was so, then a covalent bond would form between them. After several months on an A level chemistry course, Annie described covalent bonds in terms of electrons being shared and realised that one result of electron sharing was that atoms acquire "full shells" of electrons. Towards the end of her course Annie was interviewed again. She could describe the electrostatic attractions between atomic nuclei and the electrons, which indicates she had moved towards an accepted view of a covalent bond. Annie's progress is reflected in the increasing sophistication of her ideas.

Taber developed a model for progression in understanding chemical bonding ideas among post-16 chemistry students. He argues that students begin these courses with a range of conceptual tools gained from earlier study of "curriculum science" and that these are developed into first an "Octet rule framework" towards a "minimum energy explanatory principle" which uses ideas based on simple quantum theory using atomic orbitals. A key point is that his evidence supports students finding it easier to acquire or add new conceptual tools to the old set, rather than to dismantle existing models. Barker's study supports this - although students will have been taught "new" ideas based on atomic orbitals, in answering her question about molecular structure existing models for explaining molecular structure were used in preference. Even if students had "learned" the new material, they still retained their existing models. Thus, there seems to be an issue here in encouraging students to assimilate and apply new information.

Associated difficulties

In learning about covalent bonds students also find out about the shapes of molecules and that almost all covalent bonds are polarised. In addition students are presented with "rules" of combination, for example, the "Octet rule" which predicts, in a limited way, the maximum number of electrons permitted in any atomic orbital. Thus, besides learning the basic chemical idea about electrons being shared, students are also expected to assimilate many other associated concepts. In their work with Australian 17 year olds, Peterson and Treagust (1989) found that students' ideas developed during an advanced chemistry course, but their progress was often accompanied by misconceptions about these associated areas. For example, they found that 23% of 17 year olds thought that electrons were equally shared in all covalent bonds, while about one-quarter attributed the shape of molecules to repulsion between the bonding pairs of electrons, or to bond polarity. Only about 60% of students knew the correct position of the electron pair in a bond between hydrogen and fluorine. The same question asked of first year university students studying chemistry (Peterson, 1993) yielded a 55% correct response, implying that most students who learn about bond polarity retain their knowledge.

9.2 Ionic bonds

The basic ideas associated with ionic bond formation involve the transfer of electron(s) between two electrically neutral atoms to make ions with overall positive and negative charges. The number of electrons transferred or accepted by an atom is related to the valency of the element. The positive and negative charges are “ all over” the ions, so depending on the packing arrangements ions form ionic bonds with more than one ion of opposite charge at a time, forming a giant structure we call a crystal.

Students find ionic bonding hard to learn, describe and explain

Emerging evidence suggests the topic is problematic for students and that these difficulties could present significant obstacles to understanding. Barker’s (1995) study provides preliminary evidence for students’ difficulties from a rather broadly phrased question probing the formation of ionic bonds between sodium and chlorine atoms. The question comprised a diagram of a gas jar containing chlorine into which a piece of hot sodium metal was lowered together with a description of the reaction. Students were asked to explain what was happening in the jar. At the beginning of the study, about 20% gave answers suggesting they knew about ionic bonds, including the response “ an electron is transferred from sodium to chlorine and a stable compound forms” . A further 54% at this stage suggested simply that sodium and chlorine are “ reacting” or “ forming a compound” . By the end of the survey, despite receiving teaching during the intervening fifteen months, these figures were only 34% and 48% respectively, compared to much higher figures (reported above) for covalent bonding.

At a more specific level, Taber’s interview work (1993a and b) with Annie also indicates problems. Annie began her A level course by recognising a class of bonds found between metals and non-metals which she called "ionic". Annie could not recognise the bond type present in a diagrammatic representation of a sodium chloride crystal, describing this as "just sodium and chlorine atoms" arranged "in rows" (p 18). Taber summarises her view of sodium chloride:-

> "... the structure is held together, but without any bonding; there are charges on the neutral atoms; atoms are combining without overlapping; and the atoms are exchanging not just electrons but force pulls related to the electronic configuration." (p 19)

In her second interview, Annie identified the ions in sodium chloride, but used the term "molecule" to describe ionic substances, as though the elements combine to form discrete particles just as carbon and hydrogen atoms combine to form a methane molecule. Annie knew that when ions combine, the overall effect produces something neutral. In her final interview, Annie recognised that electron transfer is involved in ionic bonding, but she remained confused about whether any sort of bonding existed in sodium chloride, explaining:-

> "... it's almost like they're mixed but they haven't combined. I think they're held together just by the attraction of their forces in effect."
> (p 23)

Annie knew that positive and negative charges implied attraction, but could not describe accurately their role in the sodium chloride structure.

Barker’s responses suggest that 16-17 year old chemists cannot describe ionic bonding accurately, while Taber’s work provides detailed evidence explaining why this could be. Further details of students’ problems are discussed.

Ionic compounds form discrete molecules

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.

Students in the Australian study were asked to describe what would happen when sodium chloride was dissolved in water. All students responded that the particles would be dispersed, although some thought that sodium and chloride ions would still attract one another so there would be a "residual" structure in the water. Two students suggested that the salt would react with the water, forming sodium, chloride, hydrogen and hydroxide ions. Barker (1994) reports similar findings. She found that about 28% of beginning A level students and 40% of the same group completing their course intuitively visualised hydrochloric acid as hydrogen chloride molecules in solution. Students used the idea that the elements “ swapped partners” with chlorine to explain hydrogen gas displacement on addition of magnesium metal. Extrapolating these responses suggests that magnesium chloride molecules in solution would be the product.

Taber (1998) found evidence which indicates a possible explanation for this thinking. His detailed work led to the suggestion that students perceive ionic bond formation in terms of the electrovalency of the atoms involved. In this model, sodium chloride exists as molecules of "NaCl" because sodium and chlorine both have electrovalencies of one; a sodium atom loses one electron which is gained by a partner chlorine atom and the two ions form a discrete pair. Similarly, magnesium chloride exists as $MgCl_2$, because chlorine (valency one) combines with magnesium (valency two), allowing each magnesium atom to lose two electrons, one to each partner chlorine atom. The model essentially means that students view ionic bond formation in the same way as covalent bond formation, with the key factor being the generation of "full electron shells". Shells can be filled by sharing or transfer of electrons - either results in a discrete molecule, the formula being determined by the valencies of the elements. Taber reports one consequence of this - a student argued that a sodium ion could not form six ionic bonds unless the ion had a 6^+ charge.

A "molecular framework" for ionic compounds

Taber continued his work on ionic bonding with a survey instrument administered to 370 students (1997b). These data led him to formulate a "molecular framework" which students use to describe ionic bonds. The framework comprises three conjectures called "valency", "history" and "just forces". The valency conjecture states that the number of ionic bonds an ion can form is determined by the electronic configuration; the history conjecture that bonds can only form between atoms which have donated or accepted electrons; while the "just forces" conjecture states that ions interact with other ions, but an ionic bond can only be formed between one sodium ion and one chloride ion (p 101), so these extra interactions are "just forces" not bonds. These imply belief that ionic compounds adopt a molecular structure like covalent molecules, but with ionic bonds between ions rather than covalent bonds between atoms.

9.3 Intermolecular bonds

Intermolecular bonds do not normally feature in pre-16 chemistry courses in the UK. Ideas about hydrogen bonding, other types of dipole-dipole bonds including those frequently termed "van der Waals' forces" are taught in post-16 courses. The topic has received relatively little attention from chemical education researchers.

9.3.1 Hydrogen bonds

Hydrogen bonds arise when hydrogen is bonded to the highly electronegative elements fluorine, oxygen and nitrogen. For example, in hydrogen fluoride, the electrons in the covalent bond between hydrogen and fluorine are distributed towards the electronegative element, distorting the electron cloud and creating permanent positive and negative charges on the molecule, referred to as a "dipole". The hydrogen nucleus contributes the positive charge and the distorted electron cloud around the fluorine atom takes a negative charge. The positive charge from one molecule may align with the negative charge on another, resulting in a specific type of electrostatic attraction called a "hydrogen bond".

Progression in the development of basic ideas

Students’ thinking about hydrogen bonds has been explored by Barker (1995) and Taber (1993a). In Barker’s survey, 250 beginning A level students were asked to identify the bonds between water molecules and to explain what distinguished these from covalent bonds. At the start, about 18% identified these as hydrogen bonds, increasing to about 69% fifteen months later. About 20% began by suggesting the bonds were “ liquid” bonds or “ weak” bonds between molecules, possibly because a lack of formal teaching led to guessing from the diagrams provided. About 8% at the first stage described hydrogen bonds as “ an attraction force, not a bond” . Fifteen months later, few students gave the “ liquid/weak” bond response, but 24% gave the “ attraction” description. This suggests that students are taught to distinguish between intermolecular bonds and other types of bond, and ascribe these different properties. This is neither chemically accurate or necessary.

Taber’s work with Annie (1993a) gives a more specific view of progression in understanding of hydrogen bonds. Annie was presented with a diagram representing a chain of hydrogen fluoride molecules. The molecules were shown with the appropriate distorted electron cloud, and were drawn touching one another. Annie did not think any bonding was present between the molecules. Taber suggests this may have been because the shapes did not overlap one another. In her second, post-teaching interview, Annie could describe the difference between the O-H bond within a water molecule and the bond between two water molecules:-

> "You've got the two hydrogens added to an oxygen. And then the hydrogen brings a small bonding between like another oxygen, to hold the structure together but it's not like, it is a bond, but it's not as strong, as like, the ionic bond would be" (p 42).

In her third interview, Annie talked about hydrogen bonds involving lone pairs of electrons and demonstrated much clearer understanding of the intermolecular role of hydrogen bonding.

9.3.2 Other intermolecular bonds

Other, temporary dipoles arise because electrons continually move around within molecules. Temporary positive charges bond with temporary negative charges. This type of interaction can be called a “ van der Waals’ force” . Each electrostatic attraction is small in energy terms, but when thousands or millions are being made and broken their effect on the structure and function of a substance is significant.

Barker explored students’ thinking about intermolecular bonds other than hydrogen bonds by asking students to explain why the vapour at 1000 ^{o}C above a mixture of titanium(IV) and magnesium chlorides comprised titanium(IV) chloride only, given that titanium(IV) chloride is “ covalent” and magnesium chloride “ ionic” in nature. At the start, only 1% of respondents suggested that intermolecular bonds between titanium(IV) chloride molecules would break, a figure which increased to 16% fifteen months later. Initially, beginning A level students divided mainly among those who thought that covalent substances have lower boiling points, so more heat was needed to vapourise the magnesium chloride (22%); ionic bonds can’t be broken by heating (13%); covalent bonds are weaker than ionic bonds so break (24%) and those giving no response or an uncodeable response (33%). By the end of the study these responses were still prevalent; the figures giving these answers were 14%, 15% and 31%, with 11% giving an uncodeable or no response. These data point to the widespread use of qualitative and vague ideas focusing on the behaviour of substances, despite the fact that the course followed by these students presented all intermolecular bonds in a chemically correct, context-led way.

At her first interview, Annie (Taber, 1993a) was asked about the structure of iodine. She explained that iodine molecules were held together by "forces of pressure", not chemical bonds. After teaching, she was aware of the existence of van der Waals' forces, and correctly placed these between iodine molecules, but thought that they would also occur in compounds like sodium chloride, as though she was applying them to any structure which she could not otherwise explain. Annie knew at this second stage that van der Waals' forces would be affected by heat, but could not explain this in an accepted way. In her final interview, Annie retained the idea that van der Waals' forces existed in sodium chloride, and realised that these bonds would break before covalent bonds when a substance was heated. Annie’s views support those reported in the large scale study.

Associated difficulties

In learning about intermolecular bonds some students develop misconceptions. One common error touched on by Annie and reported more formally by Peterson and Treagust (1987) is misunderstanding of the different locations of inter- and intramolecular bonds. About 23% of students thought that intermolecular bonds were within a covalent molecule. In his later study, Peterson (1993) found that 36% of first year university chemists thought that silicon carbide had a high melting point because of "strong intermolecular forces".

Students also misunderstand the relative strengths of inter- and intramolecular bonds. Peterson and Treagust report that one-third of their sample of Australian sixth formers thought that "strong intermolecular forces exist in a continuous covalent network" (p 460).

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”.

Second, several references have been made in this section to the use of language in teaching this topic. For example, students adopt anthropomorphic language when describing the behaviour of atoms. A hunch suggests that this is not entirely of their own invention. Often, in the drive to make a topic “understandable” to all students, we slip into this language with the aim of helping, certainly not with the intention of making something harder in the long term. Clearly, however, shaking off this type of thinking, such as focusing on carbon in a molecule “wanting to make four bonds” is difficult for students. We should try to avoid this as sloppy and unhelpful in forming accurate chemical thinking. A second example relates to the use of specific terms in teaching chemical bonding. The use of the word “attraction” in teaching about hydrogen bonding could only have come from teachers, as the course materials studied by the students in Barker’s study do not use it. The distinction being made is quite unnecessary, and may only fuel students’ support for the ideas Taber found in describing ionic bonds as “just forces”.

Third, there is clear evidence that pre-16 teaching presents post-16 chemists with difficulties. One student in the Barker study was able to cite a table she had learned in her pre-16 course packed with vague statements such as “covalent compounds have low boiling points” in order to answer examination questions at that level. She went on to explain in an interview how this had caused her real problems when presented with new material at A level, as this provided no foundation. My argument here is that we do our pre-16 students a great disservice in teaching chemical bonding in such a qualitative way early on, and that greater confidence and clarity of understanding could arise from adopting an entirely different approach.

9.5 Suggestions for progress

Taber’s viewpoint that students do not dismantle old conceptual tools but add new ones is important. In applying this to chemical bonding, we need to build up a functioning correct set of conceptual tools which can be added to, rather than compromise with vague, anthropomorphic statements centred on a false rule. Although this is much easier said than done, I would like to make three suggestions.

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 emphasise 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.

Second, in teaching bond types, terminology should be consistent and clear. There is no need to use terms such as "van der Waals' forces", "London forces" or "dispersion forces" in teaching intermolecular bonds. If the first point above is accepted, then these terms become defunct, because what is needed is language which allows students to apply the "nuclei and electrons" strategy in a consistent way. Thus, "permanent dipole-permanent dipole bonds" and "induced dipole-induced dipole bonds" can be presented as terms which have genuine meaning and can be applied easily to unknown molecules. Alongside this, the idea that "bond breaking requires energy" can be reinforced, as students can be presented with data indicating relative bond energies. This will enable them to make accurate judgements about the effects of external conditions on a substance, rather than be forced to utilise vague pre-16 notions linking boiling points and bonding.

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.

Another, related but more formal approach might include the use of a diagnostic test instrument to assess misconceptions. Tan and Treagust (1999) developed a multiple choice test for use among 14-16 year olds. The nine questions are linked to known misconceptions about chemical bonding so as part of a teaching strategy could prove extremely useful. The authors also provide a detailed concept map for chemical bonding (p 77) which teachers may find helpful as a guide to indicate links between different aspects of the topic.

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.

10.1 Energy is released when chemical bonds form

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. Students' ideas about burning were discussed earlier. These reveal that many 15 year olds do not know where the heat produced in burning comes from. Chemical bonding provides them with an answer. Ross (1993) suggests that to assist students, teachers should present the reactions between fuels and oxygen as a "fuel - oxygen system" and help them to develop ideas about the relative strengths of covalent bonds in different molecules.

Support for the persistence of these ideas among post-16 chemists comes from Barker’s (1995) longitudinal study. Students were asked to explain where the energy comes from when methane burns. Initially, only 6% of students (aged 16) said that the energy was from bond formation. Other incorrect or descriptive answers included; energy is stored in methane (13%); from burning the methane (14%); from the flame (7%) or simply “ from the methane” (6%). Fifteen months later, about 50% said the energy came from bond formation. Alongside this, though, the proportion thinking that energy was stored in the methane also increased, to about 19%. All the other incorrect responses showed a marked decline. Additional evidence indicated some students recalled “ fuels are energy stores” from their pre-16 courses and found this difficult to replace with chemically accurate thinking.

In a second question, Barker asked students to select the energy level diagram they thought best represented the exothermic reaction between sodium and chlorine. Three diagrams of exothermic reactions were given - one highly exothermic reaction, another a giving out very little energy and the third mid-way between the top and bottom. The highly exothermic reaction was the “ best fit” response, but no supporting data were given, so in analysing responses either of the two relatively more exothermic diagrams were accepted as correct. Initially, only around 12% selected an appropriate diagram supported with an acceptable reason, while about 30% chose an appropriate diagram but gave incorrect or simple descriptive statements including “ the reaction is exothermic” . About 14% misunderstood the term “ exothermic” , so selected the diagram with the very small energy difference, explaining “ the reaction doesn’t give out much energy” or “ the reaction needs lots of energy to start” . About 5% connected the stoichiometry of the equation for the reaction to the arrow lengths, so selected the mid-point diagram arguing that this represented a 2:1 ratio. Fifteen months later, marked changes were apparent. About 28% gave an expected response together with a correct explanation. A further 40% chose a correct diagram without explanation. The proportions giving the other responses remained almost unchanged.

10.2 Energy is conserved in chemical reactions

Brook and Driver (1984) found that less than one in twenty 15 year-olds used ideas about the conservation of energy in written responses. When asked more directly about this principle, two-thirds of the students said, "Energy is used up or lost". The authors concluded

> "...including an explicit statement of the principle of conservation of energy in the question stem does not have much effect on the pattern of responses." (Brook and Driver, 1984, p 12).

Finegold and Trumper (1989) found similar difficulties in their study of 14 - 17 year olds. They report that 80% of their 14 and 15 year olds did not conserve energy in responding to basic questions. Energy being "used up" was commonplace. Ross (1993) notes that students acquire this idea from everyday experience of batteries going flat, petrol tanks needing refilling and electricity being "used up" in providing heat and light.

Some students in Finegold and Trumper’s study described energy as being "caused" by something, for example:-

> "Student: I think something is supplying, that causes energy...
> Teacher: I don't understand.
> Student: For all energies there is something that activates them, that gives the strength" (p 106).

This student seems to suggest that energy is made by something. The authors do not give the exact proportion of students with this view, but say the response is used "frequently" (p 103).

10.3 Entropy increases to a maximum in chemical reactions

The essential principle of the Second Law of Thermodynamics is that disorder, or entropy, increases when a chemical reaction occurs. An alternative statement is that "heat will not flow spontaneously from a colder to a warmer body" (Freemantle, 1987, p 177). Duit and Kesidou (1988) studied 13 - 16 year olds' understanding of this statement of the Second Law. They report interviews with fourteen German students aged 16 years. A significant finding was that:-

> "Most students have intuitively the correct idea that temperature differences tend to equalise and that the processes will not totally run back after equalisation." (p 193).

The principle embodied in the Second Law does not seem to run against students' everyday experiences, so perhaps this idea is less problematic. The First Law is more problematic because the energy transfers included in a system are frequently invisible; for example, a toy car when wound up will only run for a limited period of time and to a child it seems that the energy has simply "run out" or has been "used up". That the energy has done work in making the car move against the environment is not obvious. In contrast, students are more likely to think that heat can only go in one direction, since again this fits with their every day experience.

10.4 Implications for teaching

We see that the basic notion that energy is conserved is not well-learned. Instead, students focus on the visual “ evidence” that energy is used up. The problem here is perhaps more general than with chemistry alone - teaching energy as energy transfer is extremely important in developing the idea that in fact energy is not “ used up” , but moved from one form to another. From this the idea of entropy can be developed and so the factors controlling chemical reactions can be appreciated.

There are clear links between the difficulties students express in learning basic thermodynamics ideas and pre-16 chemistry teaching. The focus pre-16 is on learning in a qualitative way about the behaviour of fuels, and so to make this palatable we say that fuels are “ energy stores” and that “ energy is released when fuels burn” . Evidence presented here shows that these statements do not help post-16 chemists, but instead propagate the message that “ energy is released when chemical bonds break” . Suggestions for changing this approach are made in the next section.

There is evidence supporting the data describing the difficulties students experience with ionic bond formation described earlier. The source of energy in fuel-oxygen systems appears relatively well-known by A level students completing their course compared to that in a simple two-element reaction forming an ionic bond. This indicates that teaching at this level may need to reinforce the connection between energy release and bond formation for all bond types, rather than focus on covalent bonds. Teaching ionic bond formation seems to be managed differently from covalent bond formation, resulting in a contrast in understanding for these two bond types.

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.

The " spreading out" principle captures the essence of entropy, so effectively I propose teaching this much earlier than is done at present. The qualitative ideas are not difficult and make a lot of sense when coupled with conservation. Another approach for introducing entropy qualitatively is suggested by the Salters Advanced Chemistry course (Burton et al, 1994). This adopts the idea of " number of ways" in which particles can be arranged, leading to the fact that the most likely event will be the one which occurs. In introducing entropy using this scheme, I began by encouraging students to think about the chances of everyday events occurring, and listed about ten of these on a board. The events included the chances of winning the National Lottery, the Queen Mother living to be 100, my favourite football team winning the English Premiership, Manchester United winning it and so on. I encouraged students to offer " odds" for these. Then we went through the list discussing what the most probable result would be. Students were encouraged to think about how chance affects the outcome; for example, the odds of winning the UK National Lottery are about 14 million:1, so the most likely event is that one would not win. The same reasoning was then applied to chemical events. The Salters approach considers mixing first - there are more ways that bromine molecules and air particles can mix than exist separately, so the chances are they will mix; dried beans and peas in a jar can start off in two separate layers, but if the jar is shaken, there is only one perfect separation, so the most likely event is that shaking will result in a mixture. The mixing principle is also illustrated using a game involving two sets of six numbered counters and two dice. Two students play together, each looking after one set of counters and one die. The counters begin on opposite sides of a dividing line. When a die is thrown, the player swaps his/her counter corresponding to the number on the die with the same numbered counter of his/her partner. The result is that the counters are mixed randomly. After a certain number of throws, students are asked to note the arrangement of counters. They see that there is only one way in which the counters are perfectly separated, but many in which they are mixed together. Linked to chemical reactions, these games illustrate the point that " the most likely event is the one which will occur" and specifically to energy that the " packets" or quanta of energy tend to spread out.

Pre-16 teaching about fuels must also be changed. We must focus on the principle of a fuel-oxygen system, rather than fuels alone. The phrase " fuels are energy stores" must be removed from our language. Biologists contribute problems with their tendency to say " ATP has a high energy link which is broken and releases energy" . Colleagues need to work together to find appropriate language for this. In addition, we need to help students focus on energy being required to break chemical bonds. One approach I have used to help with this is " molecular murder" . In introducing thermodynamics many students carry out an experiment which involves burning liquid fuels, heating water and calculating erroneous energy changes. In many ways this is a good experiment, but to make the most of it I suggest using related fuels, such as the alcohols, rather than comparing say, hexane and ethanol. Using a sequence allows students to play " molecular murder" effectively. To do this, students are divided into groups. Each group is given a different fuel, although some duplication across a large class may be needed. Either before or after the practical experiment, students are asked to name their fuel for themselves and to make a model of one molecule. They then have to work out what happens when the fuel molecule burns. Models of oxygen molecules will be made. They then realise that to make anything happen the fuel molecule and oxygen molecules need to be torn apart. This sounds rather grim, but I encourage students to put as much energy into " murdering their special molecule" , that is ripping the model to pieces as possible. This makes the point that energy is needed to break bonds. We say that in fact all bonds of the same type require (within limits) the same amount of energy to break. This makes sense. When all the atoms are separated, new bonds can form and so the natural question to ask is, " If we put energy into breaking bonds, what must happen when they form?" Although we cannot " see" the energy released in building new models, students grasp the idea of bond formation being a reverse process, so realise that this involves energy release. The precise calculations can be carried out using a simple spreadsheet, which reinforces the point that combustion is always exothermic.

Thirdly, we need to revisit teaching ionic bond formation. In teaching thermodynamics, specifically Hess' Law, we focus almost entirely on covalent molecules, and in particular, fuel-oxygen systems. In teaching ionic bonding, we use Born-Haber cycles, but do not explicitly make the link to Hess' Law. These are presented to students as two distinct systems. To help reinforce the point that bond making is exothermic, we need to approach the teaching of these bond types and the application of thermodynamics ideas in a much more consistent way than is traditionally done at present.

11 Students' ideas about chemical equilibria

A traditional teaching pattern for chemical equilibria suggests that pre-16 students are introduced to a "two-way" reaction treated qualitatively, while more complex ideas such as calculation of equilibrium constants and the meaning for these feature in post-16 courses. Le Chatelier’s Principle (LCP) is introduced commonly at this stage to help students predict the direction of change in equilibrium position. The ideas associated with chemical equilibria are commonly regarded as among the most difficult to teach and learn in pre-university chemistry courses, so perhaps unsurprisingly the topic has received extensive attention from researchers keen to explore the development of students’ thinking about the key concepts involved. The key points are reviewed here.

11.1 Issues in learning about chemical equilibria

11.1.1 A “dynamic” equilibrium

The most basic principle students need to understand is that an equilibrium position implies molecules exchanging between two “sides” at the same rate. The “sides” may be two phases, for example, the distribution of iodine molecules between water and hexane, or two reactions, such as occurs in the formation of ammonia. The dynamic nature cannot be seen, but is implicit in the chemical events.

Maskill and Cachapuz (1989) used a word association test (WAT) to investigate students’ intuitive responses to the statement “the reactions were at equilibrium”. About 76% of 14-15 year olds who had not received teaching about equilibrium strongly associated this with “static” and “balance”. Little change was observed post-teaching, as this student’s response illustrates:

> “...the reaction is finished, it is stable, it will not react anymore unless you add something...” (p 67)

Gorodetsky and Gussarsky (1986, 1990) found similar reasoning among students aged 17-18. Their earlier study used WATs in conjunction with a teacher-administered test. They found that only the highest achievers on this test broke the link between “dynamic” and “static” to make the associations between “dynamic”, “chemical equilibrium” and “reversibility” instead. The authors’ later work explored the impact of a teaching sequence on students’ thinking, comparing a control group who received no tuition with two groups receiving teaching to different depths. Their results indicated that the teaching resulted in links between “equilibrium” and “chemical equilibrium”, but also a slight increase in the association of “static” and “state of balance” to both these terms. These data suggest that the notion of a reaction in which continued unobservable change is occurring is counter to intuition, so many students find this difficult.

11.1.2 An equilibrium reaction involves two separate reactions

Experienced chemists consider the forward and reverse reactions part of the same chemical system. Evidence suggests that students cannot do this, but view the two reactions as separate and independent events. Early evidence for this came from Johnstone et al (1977), who report that 80% of 255 16-17 year old students has this view. These researchers suggest that the double-headed arrow used in equilibrium reactions contributes to the “ two-sidedness” students perceive. One arrow, used in a reaction which goes to or near completion, emphasises one reaction, so two arrows implies two separate reactions.

More recent evidence for this reasoning comes from Gorodetsky and Gussarsky (1986), who found similar reasoning among about one-third of 17-18 year old chemists; Cachapuz and Maskill (1989) from their word association tests (WATs) used with 14-15 year olds; and Banks (1997) who tracked the developing understanding of a small group of post-16 chemists through an A level course.

11.1.3 Problems with Le Chatelier’s Principle

In 1888 Henri Le Chatelier devised a summary statement which could help chemists make qualitative predictions about changes in equilibrium position:

> “ If a system is at equilibrium, and a change is made in any of the conditions, then the system responds to counteract the change as much as possible”
> (Burton, et al, 1994, p 137)

Several workers have probed students’ ability to apply LCP to situations in which additional reagents are added to a closed system. Hackling and Garnett (1985) found that although about 40% of 17 year olds could apply the reasoning expected, a common misconception was to treat all substances in the reaction independently, rather than viewing the interactions between them. Bergquist and Heikkinen (1990) report some 19 year old chemists using an “ oscillating” model, suggesting that when one change has occurred, another must follow immediately because the first position has altered. They report, with no precise percentages, that a common idea was the notion of the equilibrium being re-established only when all the additional reagent was used up. These ideas reflect students applying a “ two reactions” model for chemical equilibrium - in this latter case, if a reagent was added, then the forward reaction would continue to “ use up” the extra material, while the reverse reaction remained unchanged.

The limitations of LCP also present problems. Wheeler and Kass (1978) noted that 95% of their ninety-nine 17-18 year old chemists misused LCP, not realising that it cannot be applied in all situations. Quilez-Pardo and Solaz-Portoles (1995) studied the responses of sixty-five teachers and 170 students to five situations in which LCP did not apply. Between

70-90% of students and around 70% of teachers used LCP in answering these questions, resulting frequently in incorrect predictions.

11.1.4 Calculating and using equilibrium constants

The value of K indicates the extent of a reaction and is calculated by applying the Equilibrium Law. The higher the value of K, the more complete the reaction. K is constant for a specific reaction at a defined temperature. A number of studies reveal students' difficulties with these ideas.

One difficulty reported by Hackling and Garnett (1985) is that about 50% of 17 year olds think that there is a simple arithmetic relationship between the concentrations of reactions and products at equilibrium, most commonly, that these are equal. The authors suggest that:-

> "This misconception can probably be attributed to the considerable emphasis placed on reaction stoichiometry in introductory chemistry topics."
> (p 211)

Students will be aware that chemical equations must be "balanced" and transfer this idea when they consider an equilibrium position.

A second, given by about 20% in the same study, is that K increases when equilibrium is re-established after changing concentration of a reactant. Students argued that this would result in more product and hence a higher value.

Thirdly, Hackling and Garnett and Gorodetsky and Gussarsky (1986) found that many students did not appreciate the effect of temperature on K, demonstrating an inability to judge when K is constant, or when and how K changes. The proportions expressing these ideas decreased post-teaching. In a small-scale study using a context-led chemistry course, Banks (1997) revealed little change in students' thinking about K, with many remaining uncertain about when K changed.

11.1.5 Confusing rate and chemical equilibrium

At equilibrium, the rates of the forward and reverse reactions are equal, resulting in the dynamic " no overall change" position. Although this appears quite straight-forward, the literature reveals several ways in which students confuse rate of reaction with chemical equilibrium ideas.

Hackling and Garnett's (1985) post-teaching study with thirty 17-year old chemists revealed that about 25% thought the rate of the forward reaction would increase from the time reactants were mixed until equilibrium was established. This may reflect the perception of the forward and reverse reactions being separate events.

Cachapuz and Maskill (1989) and Hackling and Garnett (1985) find some students who consider concentrations of reactants and products are equal at equilibrium. These students may be directly confusing equality of rate with concentration.

Thirdly, Hackling and Garnett report that about 50% of students think that changing conditions results in an increase in the rate of the favoured reaction and a decrease in the rate of the other reaction. Banerjee (1991) found similar reasoning among 35% of undergraduate chemists and 49% of chemistry teachers. Some students (27%), extended this to the role of catalysts, suggesting that the rates of forward and reverse reactions would be affected differently, a finding corroborated by Gorodetsky and Gussarsky (1986).

Finally, Banerjee reports (without figures) that both undergraduate chemists and high school teachers tend to associate a high K value with a very fast reaction.

11.2 Implications for teaching

Students' " everyday" experiences of chemistry contribute to the problems they experience with chemical equilibria. They see reactions which, to them, go to completion and are not encouraged to think that the reverse reaction may be taking place. This is perhaps unsurprising, since up to the age of 16 the preceding sections have indicated that students have poorly developed ideas about chemical change, conservation of both energy and mass and particle ideas. In pre-16 courses we also tend to choose chemical reactions which most suit our purposes of being relatively easy to follow, in terms of representing as chemical equations, measuring colour, temperature or gas production and those which occur in a timescale to suit the duration of an average lesson.

Hackling and Garnett (1985) suggest that students' confusion between rates and equilibrium fits this pattern. For example, when magnesium ribbon dissolves in hydrochloric acid, the reaction appears to speed up since the metal is coated with an oxide layer which must first be dissolved before the metal and acid can react. Students will not perceive the oxide layer, but will notice that the reaction becomes more vigorous with time. The reaction between calcium carbonate and hydrochloric acid is used commonly in rates experiments. The production and emission of carbon dioxide gas prohibits the reverse reaction, so students are led to think of the reaction as one-way.

Le Chatelier's Principle is widely taught in post-16 courses, tending to become a mantra used in answering all questions on equilibria. Examination boards in the UK have made a point of including questions using LCP in A level, contributing to the dominance of this approach in considering equilibrium problems. The result is that students are not able to use any other type of reasoning, in particular from thermodynamics perspectives, so may conclude their studies with erroneous thinking.

The basic idea of a dynamic equilibrium depends on students having a working particulate model for chemical change. Previous discussion indicates that this may be in the process of developing, at best, among teenage chemists. The persistence of a continuous view of matter presents a serious obstacle towards correct understanding of chemical equilibrium ideas.

11.3 Suggestions for progress

Pre-16 teaching needs to present students with a wider range of reactions than is demonstrated currently. We should not be afraid of showing situations which do not meet and expected " norm" , but rather use these as ways to challenge thinking and promote a wider perspective on chemical events than the one-way reactions in popular usage permit. Demonstrations of " unusual" reactions could form part of a teaching sequence designed to challenge students' perceptions of chemical change, encouraging them to accept an equilibrium occurring in a qualitative way.

The widespread application of LCP in post-16 chemistry deserves to be challenged and replaced with a much clearer, more accurate and essentially more honest approach to considering equilibrium problems. Banerjee (1991) is quite right to advocate teaching the laws of van't Hoff, which are based on thermodynamics, to which I would add use of the Equilibrium Law. LCP should be regarded as redundant - it is unnecessary and unhelpful. However, before consigning LCP to the chemical equivalent of dust, I should report the results of Treagust and Graeber (1999)'s study comparing two different approaches to teaching equilibrium. The effects on students' learning of the Australian approach, featuring LCP and rates of reaction taught using analogies and the German, using the equilibrium law and analogies in only the final lesson of a teaching sequence were compared. The results showed no significant differences.

Students' difficulties with the equilibrium constant deserve attention. There is a need to establish the mathematical relationship between the value of K and the concentrations of the reactants and products. Students need to experiment with figures to see for themselves that changing concentrations does not result in change to K. Once this is firmly established, students then need to work out why temperature affects K, but changing concentrations does not. Teachers need to introduce and explain the effects of changing temperature in relation to the enthalpy change for the reaction, but to prevent students from adding in rates ideas. Awareness that this might occur should help teachers be cautious and careful in the language used.

Voska and Heikkenen (2000) have devised a " Test to Identify Students' Conceptualisations" (TISC) about aspects of chemical equilibria, specifically, the application of LCP, constancy of the equilibrium constant and the effect of a catalyst. The test adopts a two-tier multiple-choice approach. The authors suggest that although open-ended questions may assess students' reasoning more accurately, the multiple-choice test does allow teachers to identify a range of misconceptions requiring remedy (p 171). Despite their limitations, diagnostic tests may be useful in determining students' starting points, their progress and change in thinking post-teaching.

12 Discussion

Here my intention is to draw threads together which have run through the previous sections and to make suggestions for future work. I will discuss several issues: the difficulty and importance of going " beyond appearances" ; the need for very good basic teaching pre-16; the importance of developing mathematical skills and the possibilities for future research.

I entitled the report " Beyond Appearances" because that is how chemists approach the world: in terms of the unseen particles which make up substances we need and use everyday. This is so instinctive to a chemist that s/he cannot " not see" particles. A professional chemist I met recently showed me his PhD thesis, which described how he personally had created a new class of compounds by making over eighty new organometallic molecules. These were his work, his life, his obsession. School students cannot share this obsession because they do not possess " molecular spectacles" . Similar arguments apply to understanding energy - " seeing" this dissipated into non-useful forms is a key to accepting the First Law of Thermodynamics. These points are fundamental to genuine understanding of chemistry, but as this review indicates, are problematic and, I believe, have consequences for our subject which are seriously underestimated. When students cannot " see" particles they cannot really understand chemical reactions and so the fabric of chemistry is lost to them in a haze of impenetrable events completely at odds with their every day experiences of a " continuous" world. Perhaps the best many students can hope for is that their teacher presents the subject in a relatively interesting way permitting learning of some facts and patterns of chemical behaviour. Although this generates some professional chemists to supply our needs for the future, many students express dissatisfaction with the subject as Osborne's and Collins' (2000) recent report suggests. Action is required. I cannot pretend that I have the answers, but my intention in writing this report has been to make a contribution by starting (or continuing) a debate about how to proceed.

A number of references have been made to pre-16 teaching strategies on chemical learning. I will make two points about these. First, I fully accept that delivery of the National Curriculum requirements is a prime goal for UK pre-16 teachers, so what is presented in chemistry lessons reflects the prescribed content. Also, many of the comments about how we teach these topics in pre-16 courses apply to us all - I have clear memories of teaching year 10 lessons involving students compiling a table comparing the boiling points and structures of covalent and ionic compounds and teaching ionic bonds in way which might generate a " molecular framework" . This is just how things have been done up to now. My second point is that we must take account of the misconceptions research and move on to new approaches. The remainder of the discussion sets out what this might mean.

The evidence indicates that one reason for the impact of current pre-16 teaching is that students find it very difficult to " unlearn" an idea. There are many references throughout this report which suggest that students' earliest experiences of chemistry have very significant and far-reaching effects, often influencing at least their work at A level. Taber (1997a) reflected on this, noting that students never seem to dismantle old ideas about chemical bonding, but instead prefer to add new thinking. We also see evidence for this in learning about fuels and hydrogen bonding. Of course, for many students this results in confusion and poor understanding. The challenge for teachers is therefore to develop ways of teaching the very basic principles, particle theory and chemical change very well. By " very well" I mean in ways which do not " skim the surface" of students' thinking, but provide intellectual challenge to help develop the " molecular spectacles" needed for further study. If students cannot " unlearn" ideas, then we should teach the chemistry we really mean them to know right from the beginning. The compromise of the current " soft-sell" position is proving to be fruitless.

We need also to take one other point more seriously than I believe we do at present. That is, chemical concepts seem to divide neatly into those we could call " qualitative" and " quantitative" . By " qualitative" concepts I mean those which do not require additional skills from outside the subject, particularly mathematics. In this category I would place particle theory, changes of state, chemical change, (including acids and bases and elements, compounds and mixtures) and chemical bonding. These can be taught without recourse to mathematical skills beyond the simplest processes. " Quantitative" concepts use higher order maths skills such as proportion and ratios, logarithms and probability. My point is that besides teaching the basic qualitative concepts well, we also must make sure that students have the necessary skills from outside chemistry to cope with the extra demands made by the quantitative areas. I am aware that " maths for chemists" and calculations books are in increasingly abundant supply, but I also wonder about the extent to which we grasp how significant students' struggle with mathematics in chemists really is. So, to teaching the basics well, I would also add a need to develop students' skills in handling mathematical aspects very carefully and thoroughly.

Finally, I would like to indicate possible areas for future work. This report reveals that certain concept areas have received extensive treatment from researchers, while others are relatively barren and still others, such as aspects of inorganic and organic chemistry are untouched. "Stamp-collecting" of misconceptions in these areas is required. Second, in order to improve our current teaching, there is a need to establish in much greater detail *what teachers actually do* in teaching these ideas. I am very aware as I meet chemistry teachers that there are some jewels among strategies used to teach certain ideas. We can do much more to share these, develop them and help new teachers learn them. Thirdly, I would advocate further work on developing diagnostic tests to help determine student progress in learning. Several references have been made above to tests developed by researchers. Their value lies in heightening teachers' awareness of problems in learning, so helping prevent "surface skimming" and instead maintaining intellectually challenging work. Embedding these in every day practice could be beneficial.

This report comprises an extensive review of misconceptions research in chemistry coupled with my personal views about the implications these have for teaching and suggestions for progress. I hope readers have been challenged to consider how we can implement the necessary changes to help more students go "Beyond Appearances".

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