Beyond Appearances:
Students' misconceptions about basic chemical ideas

2nd Edition

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Introduction

"Beyond appearances" began because the Royal Society of Chemistry in London considered there was a need to bring together research on students' misconceptions in chemistry. The first edition was published and is still available on the internet at http://chemsoc.org/learnnet/miscon/htm. 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.

In the intervening time between the first edition and this one I have had the opportunity to think more and to publish ideas, many of which I have used in classrooms, about how misconceptions may be addressed. The second edition came about by the kind invitation of José Antonio Chamizo Guerrero at the National University in Mexico City to translate the first edition into Spanish for publication in Mexico. Nearly four years have passed since the first edition was placed on the website, so I decided to update the original by combining work on strategies and key difficulties into the first basic report. Hence the second edition.

The premise for "Beyond Appearances" is that many students aged 11-18 are likely to have misconceptions in the basic areas listed above, as they struggle to come to terms with the abstract ideas comprising chemistry. The most significant misconceptions are described and discussed, together with, where possible, indications about the origins of these.

Achieving good, chemically accurate understanding of the concepts comprising chemistry presents teachers with a significant challenge. If this is not taken seriously chemistry will remain a mystery for many. Hence the inclusion of activities at the ends of most sections. These are intended to provide ideas for further development, but most have been tried and tested in a range of educational settings.

The final discussion makes suggestions for future work. 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.

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. Suggested activities 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.

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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).

Recent teaching, as in the Novick and Nussbaum study, generated even higher proportions. 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).

Griffiths and Preston (1992) found similar ideas. Their 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 Summary of key difficulties

Four key misconceptions about the particle theory and matter are:-

1. "Matter is continuous"

A small proportion of 16 year old students 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.

2. "The space between particles is filled"

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 notion that empty space exists between particles is problematic because this lacks supporting sensory evidence. 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.

3. *"Bonds or forces explain how particles move"*

Students may reason that attractive forces are present between gas particles and that these explain why gas particles may clump together. A student may modify this later to explain the uniform distribution of gas particles in terms of repulsive forces. In contradiction, forces may be present when the substance is gaseous, but not when solid. These ideas may contribute to difficulties for students in understanding chemical bonding.

4. "Particles can change form"

Students ascribe macroscopic properties to particles. For example, particles may explode, burn, contract, expand and / or change shape. This primitive reasoning prohibits understanding of the nature of a chemical reaction.

2.6 Suggested activities[2]

In the UK, 11-14 year olds receive formal teaching about the particle model. Their background is usually a range of ideas about materials gained from primary school. Teaching should allow children's ideas to develop by revisiting the topic and by providing opportunities for misconceptions to be expressed in a "safe" environment.

1. Be "up front" about the problem

Be honest that the invisibility of particles to the naked eye means our minds "see" materials as continuous. Explain that even scientists themselves did not understand about particles until quite recently – they had been at work for nearly 2000 years before the idea of atoms was accepted in the early 19th century.

The implication from this is that we cannot expect children to change their thinking overnight if scientists took this long to make the "discovery" themselves! Children may accept the existence of particles readily, but take a long time to assimilate the implications of this model for the behaviour of matter.

2. Make particles visual

Give children an idea of the scale of particles "smallness" by showing a range of microscope images of small items which we normally cannot see, for example, details of insects, bacteria, viruses. Ask what these organisms or items are made from. Atoms must be smaller than these! Introduce the idea of an "atomoscope" – a special microscope which can be used to look at atoms, or the idea that they have "molecular spectacles" so can "see"

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[2] The activities here were first published in Barker (2001a).

atoms. What might they look like? Ask children for their ideas, perhaps drawing pictures. Then introduce the scanning tunnelling microscope (STM) as a real life "atomoscope". Show pictures. Invite children to look at a sheet of copper metal and imagine the atoms comprising the structure. Ask them to imagine the sheet stretched to cover 50 miles from end to end and to estimate the size of the atoms in the sheet using a football, tennis or golf ball as a guide. When everyone has guessed, reveal that an atom would be approximately 1cm in diameter (in the UK the sweets called "Maltezers" are conveniently this size), much smaller than anyone will have thought!

3. Integrate particle ideas into other topics

Particle theory is often taught in isolation. This does not help students from appreciating particle behaviour in other situations. Use particle terminology when talking about chemical reactions or changes of state, for example, referring to "sodium particles" and "chlorine particles", rather than just using the element names which refer to bulk substances. For the moment, this will suffice – the differences between atoms and molecules can be introduced later. Support this with models or images of the particles. Introduce simple symbol equations as soon as possible rather than using word equations that emphasise bulk materials rather than particles.

4. Use diagnostic questions

Explore students' thinking by giving situations to explain, such as "If you pump air into a soft bicycle tyre or football, does the mass increase, go down or stay the same?". Students should select the answer they think is correct. Then actually do the experiment. A sensitive balance is required to demonstrate that mass would increase. Students will usually respond that the mass would stay the same because gases have "no mass". They will be surprised to see the mass increase, so be ready to help them adjust their thinking by encouraging the idea that particles have mass!

Examples like this can be extended to encourage thinking about particle movement. Ask what would happen to the pressure inside a tyre or football left in the sun on a hot day. Ask again if the mass would increase. This time, there is no change in mass, as no more gas has been added, but the tyre/football has become harder, just as before. So why has this change occurred? Questions and answers can be used to lead students to the idea that the pressure inside has increased and that this is caused by increased particle movement.

3 Students' ideas about changes of state

Poor understanding of the four basic aspects of particle theory affects students' thinking about changes of state. Students' ideas about this have been studied extensively[3].

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 olds 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 that particle motion increases on heating. Recall that about 40% of 16 year olds 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 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)

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[3] 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).

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. Over 700 students answered the question, giving the same responses. 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 the number offering a correct response, steam, increases between the ages of 12 and 17. However, 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. He 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), Johnson 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. These are: "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 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 commonly 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°C and left to warm to -1°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 Summary of key difficulties

1. Students are inconsistent in their use of particle ideas

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, break up and/or are static.

5. ***State changes are seen as separate events***

Students find it hard to appreciate the reversibility of the state changes, thinking of each process as a separate event. Thus, melting and freezing may not necessarily involve the same substance – we do not help by giving solid water the name "ice", calling liquid water "water" and gaseous water "steam"!

3. Information about one substance cannot be transferred to others

Water is often used as an example for discussion of state changes. Although students may be able to give scientifically correct ideas about the behaviour of water, they cannot apply the same 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 depends on one example.

4. Ideas about condensation

Students may develop a state change model that involves molecules breaking up on boiling and reforming on condensing. 12-15 year olds may not know where condensed substances come from, saying for example that they "come through the glass" or have "stuck to the glass".

5. Ideas about melting and freezing

Ice has been used commonly as the substance for investigations about students' thinking. About half of 15 year olds think ice particles can shrink, expand, dissolve or melt when changing to liquid water. Melting and dissolving are used frequently as synonyms. Ideas about freezing are less thoroughly investigated – 16 year olds seem to develop the idea that freezing and melting are "opposites". The idea that freezing must occur at "cold" temperatures seems to be firmly fixed in many students.

3.7 Suggested activities[4]

1. Provide a wide range of substances

Students need to experience state changes for more than one substance. Encourage investigation of state changes of everyday substances, for example, butter, margarine, chocolate, tomato soup. These examples may help students learn that freezing points are not necessarily "cold" and that boiling points are not always "hot". Students may experiment with finding the transition temperatures between states for a range of substances and plot these on the same graph to show the variation in values for the same state change.

2. Challenge the "molecules break up" model

Use molecular models while discussing changes of state. Boil water in front of students. Give each person a piece of paper. Tell them to write down what they think is in the bubbles when water boils. Collect the responses. Sort the responses. There is likely to be a range. Ask a few students to explain their thinking. A few will say "steam". Ask what steam is made from – water molecules. A proportion will suggest hydrogen and oxygen. Use a molecular model of ice showing the hydrogen bonds between molecules to illustrate that it is these bonds which break during state changes, not those within water molecules. Students who use the "molecules break up" model will usually change their thinking as a result.

3. Reinforce particle ideas

Use visual images to explain what happens when state changes occur. Discuss what happens to the particles – do not discuss the bulk substance, but refer to "butter particles", "chocolate particles" or "tomato soup particles". Discuss why the temperatures for transition between states differ, relating this to different types of particles and therefore different intermolecular bond strengths. For consistency and to prevent difficulties learning chemical bonding, the term "intermolecular bonding" is best, rather than "attractions" or "attractive forces".

4. Consider how to present state changes as reversible

Students need to see heating and cooling cycles for themselves, so they can realise that

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[4] These activities were first published in Barker (2001b).

nothing has been added or taken away to the substance. They may think that changes have occurred because appearances change. Re-solidified butter, for example, never looks the same as it did before melting! Using particle ideas will help students realise that the particles have rearranged in a different way so will not give a solid with the same appearance.

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. 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, for example, that 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 when 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 Atkins' definition in a confused form. 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 considered 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 °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 post-16 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 a post-16 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.

Activities to help students are suggested 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 agreed that a chemical change 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' sensory information conflicts with what is taught, creating confusion. 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 helpful to students developing 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 stimulating 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 sciences has a distinctive vocabulary of words with very specific meanings. A major part of teaching and learning chemistry is to approach this language in a way that 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 Summary of key difficulties

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. Four key difficulties are presented.

1. Student's thinking is not consolidated

The traditional 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 students have learned as the teacher intended. Little time is given to discovering children's ideas and to addressing these. As a result, students exhibit very muddled thinking as they attempt to assimilate new scientific views about the world into their own structures.

2. Reasoning about reactions does not involve particles

Students' reliance on continuous matter models leads them towards thinking about chemical reactions in the same way. Thus, bulk properties of a substance are attributed to particles – a copper sulphate particle would look blue, an atom of copper would conduct electricity and so on. Students may regard two forms of the same chemical element as different substances, due to structural variations such as those between iron wool and an iron nail. However, students show understanding of the differences between elements, compounds and mixtures when presented with diagrams, suggesting that visual images are helpful.

6. State changes are often thought to be chemical reactions

Students confuse state changes and dissolving with chemical changes. Chemists themselves do not help by arguing over details, missing the point for students! The key point required is that a chemical reaction involves making a new substance. Visual images are needed which make this clear and unambiguous rather than requiring the "leap of faith" suggested by Gensler (1970) in believing that a substance recovered from solution is the same as the starting material.

7. The language of chemistry causes confusion

Students meet many different terms in chemistry each with a specific meaning to chemists. In learning the basic ideas, these are often confused. The word "substance" for example, may be interchanged with "element" and "atom". Introduction of the terms "element", "compound" and "mixture" before students understand what happens in a chemical reaction may also create problems. Other descriptive words also cause problems. For example, the extraction of "pure" salt extracted from rock salt is not considered as purification, but producing a chemical product (Johnson,1996). Children need to be given opportunities to learn chemists' meanings rather than to be told the terms alone.

5.4 Suggested activities[5]

The Dutch educators de Vos and Verdonk (1985a, b, 1986, 1987a, b) propose a strategy for introducing chemical reactions entitled "*A New Road to Reactions*". This five-stage technique requires teachers to avoid a traditional approach based on understanding detailed terminology and instead to present chemical events so students must think of explanations for what they see.

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. The approach challenges the sequence commonly used to teach about basic chemical ideas appears to create confusion for many secondary-age students.

1. Acknowledge a new substance is formed

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 prefer intuitively to think of the two original substances as existing with the yellow stuff, but something stopped them from

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[5] These activities were published in Barker (2001c) and Barker (2002).

seeing the yellow material at the start.

With persistence 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)

2. Extend this thinking to other reactions

Students carry out the same reaction, but add small quantities of solids to water in a petri dish. 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. At this stage, students can be encouraged to think that the particles are very small, otherwise they would be seen moving through the water.

3. Show reactions involving heat generation

Allow students to 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 sodium hydroxide solution is titrated against hydrochloric acid. Students are asked to explain where the heat comes from. Work with the students towards the answer that new chemical bonds are formed.

4. Introduce the idea that particles are rearranged when chemical reactions occur

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. Students need to learn that although an atom retains its identity during a chemical reaction, a molecule does not. The making of new bonds implies that new molecules are made from the original particles. The term “atom” can be introduced later. The authors acknowledge that changing students’ thinking is difficult.

5. Illustrate the principles by decomposing malachite

When malachite is heated the “molecule” is broken down into two other substances. de Vos and Verdonk (1987b) propose using the decomposition of malachite to introduce the idea that a "molecule" of malachite can be "broken". 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.

6 Students' ideas about specific chemical events: closed system reactions

Closed system chemical reactions in which atmospheric gases are not involved are commonplace in early chemistry courses. Students’ poor understanding of the relative densities of matter and particle theory creates problems for them in realising what happens during these changes. The main examples of such reactions used by researchers are discussed here.

6.1. 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.

6.2. 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)

6.3 Dissolving

For this purpose, dissolving is regarded as a chemical change.

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.

6.4 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 that 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 lying 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 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.

6.5 Summary of key difficulties

1. Mass and density are confused

Reactions involving changes of states are difficult to explain correctly. Thus, students may reason that the products from a precipitation reaction are heavier than the starting materials; that when a gas is produced the reaction has lost mass overall.

2. Gases may pre-exist / be characteristic of a chemical reaction

Students are often shown reactions producing gases. Thus, they may connect gas production with the notion "chemical reaction" so the two are inextricably linked. Explaining how a gas forms is also problematic – gases may "pre-exist" in the starting materials for a reaction, simply being "released" when a tablet or other substance meets water.

6.6 Suggested activities[6]

Demonstrating simple reactions can be a powerful way of prompting students to change their thinking about this type of reaction.

1. Precipitation

Place two 50 cm^3 measuring cylinders on a balance. Add 25 cm^3 barium chloride solution to one cylinder and 25 cm^3 sodium sulfate solution to the other. Record the total mass. Put small amounts of the two solutions in separate test tubes. Tip one solution from one test tube to the other. Ask students to observe the white precipitate formed. Now ask them to predict what happens to the mass – if one solution on the balance is tipped into the other, what happens to the mass? Will it go up, down or stay the same? Expect that about half of a class of 14-15 year olds will say the mass will increase because a solid has formed. Next, tip one solution from one measuring cylinder to the other. Ask students to observe that the mass has not changed. Some will be disbelieving. Ask for their explanations, working towards the answer that no mass has been added or taken away, so no mass change is expected, while the density of the materials is irrelevant.

2. Making solutions

A similar strategy can be used to help students think about dissolving. Have ready fixed, identical masses of sugar and sodium chloride and two beakers of water. These solids dissolve to form solvated molecules (sugar) and ions (sodium chloride). Place one beaker and the sample of sugar or sodium chloride on the balance separately. Ask students to

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[6] These activities were published in Kind (2002a) and Barker (2002)

predict what will happen to the mass when the sugar / sodium chloride is added to the water. Some students may think that the mass will decrease either because a gas is produced or because the substance "disappears". Others will think that the mass will stay the same, but will picture the sodium chloride remaining as molecules in the water, and sugar molecules breaking up into atoms. Demonstrate first that the mass remains unchanged, then use molecular models to show students what happens to the crystal structures in each case. This demonstration provides a good opportunity to discuss the behaviour of covalent and ionic compounds and intermolecular bonds.

3. Dissolving a tablet

Add an effervescent tablet to water in a conical flask. Ask students to predict what will happen to the mass – they may readily predict that this will decrease because a gas is being given off. Placing the flask on a balance and following the decrease in mass will support this. However, they may not realise that the gas itself has mass. To demonstrate this, repeat the experiment, but place a balloon on the mouth of the flask. This will inflate with the gas and the mass will remain unchanged. The experiment shows that the products of a reaction have the same mass as the starting materials, as well as that gases have mass just like matter in any other physical state.

This reaction can also be used to discuss the origin of the gas. Show the students the names of the ingredients in the tablet and ask which is the gas. They should find that this is impossible – therefore the gas cannot have existed beforehand, but must be made in the reaction between the compounds in the tablet.

7 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).

7.1 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).

7.2 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 olds beginning post-16 chemistry studies 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.

7.3 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.

7.4 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 thinking that 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 in nature. 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 the carbon- and hydrogen-based fuels 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.

7.5 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.

7.6 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 that 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.

7.7 Summary of key difficulties

The research evidence indicates that students develop a range of faulty models about open system chemical reactions.

1. The role of oxygen is poorly understood

The atmosphere is invisible to the eye - and students' reliance on concrete, visible information means they therefore often avoid the role of oxygen in their explanations for open system reactions. Even if the role of oxygen is appreciated, the notion that gases do not have mass means that students do not realise that solid products of an oxidation reaction have more mass than the starting solid.

2. Fuels change state and do not burn

Some students develop the model that fuels change state on burning. In this model, candle wax melts and petrol turns to gas. The flame of a candle is an entity separate from the fuel and is not particulate.

3. Fuels are destroyed in burning or changed into something else

That many solid fuels produce a solid ash on burning which is much smaller in mass and volume than the original material leads to the impression that the fuel has been destroyed. Rust, produced in slow oxidation of iron, may be perceived as an active agent eating away the metal. Carbon is thought of as a product of a burning or oxidation reaction, even if this element was not present in the reactants. Similarly, fuels may transform into energy.

7.8 Suggested activities[7]

1. Use diagnostic tasks

Find out what students are thinking by asking diagnostic questions such as those used in research studies. A good way of introducing a lesson on fuels is to provide three different examples – one solid, one liquid and the third gaseous. Show students that all three burn, and ask what the mass of the products would be. Find out if they use change of state or destruction models in their answers, and if they reason consistently across all three fuels. Ask them what they think are the products of combustion in each case. Be prepared to act on their answers, perhaps using the strategies described below.

2. Use molecular models

Divide a class into groups, giving each a different fuel to consider. The group must make a

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[7] These activities were first published in Kind (2002b).

molecular model of the fuel and oxygen gas, then use these models to explain how the fuel burns. The models can be used to work out the equation for the reaction.

3. Present common ideas explicitly

Students need to realise that the products of combustion are consistent, regardless of the fuel. Combustion always produces an oxide. Work with them on understanding that gases have mass, so the products of combustion must always include the mass of oxygen. Equations can be used to support this. Show that carbon can be produced by holding a tile above the flame of carbon-based fuels – that the same products arise regardless of the fuel being solid, liquid or gaseous. The difference may be in amount – a "clean" fuel such as ethanol will generate fewer carbon particles than candle wax. Repeat the procedure with metals being oxidised – molecular models can be used to show that the metal is reacting with oxygen gas, and that therefore no carbon is produced.

4. Go back to basics

Review students' understanding of chemical reactions. Combustion is a chemical reaction resulting in the production of new substances in which mass is conserved. Using models, students can be led to realise that some energy is required to break bonds initially to start the reaction, but that after this the reaction is self-starting. Energy released when the product molecules are formed is used to break more bonds and to heat/cook/ drive a vehicle until the fuel or oxygen supply is exhausted.

8 Students' thinking about acids, bases and neutralisation

8.1 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 olds. 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 olds showing 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. Students who gave incorrect responses to the first part also used the term "displacement reaction". For example, around 8% initially drew hydrogen chloride molecules and used this phrase, a figure increasing 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.

8.2 Summary of key difficulties

1. Acids can burn and eat material away

Students think of acids as active agents that damage skin and other materials. The idea develops in young children, who learn to think of acids as "dangerous". Cartoons showing scientists making holes in benches with acids also contribute to this image. Acids are not perceived as being particulate, but rather continuous matter with special properties.

2. Neutralisation means an acid breaking down

Rather than considering neutralisation as a reaction between an acid and an alkali, students perceive this as removing acid properties. The alkali may stop the action of an acid, or alternatively the acid may break down.

3. A base/alkali inhibits the burning properties of an acid

Students tend to meet acids in formal education well before alkalis, so ideas about these chemicals are relatively under-developed. Although dilute alkalis are in fact more corrosive than dilute acids, students' perceptions are that they have no corrosive properties, instead acting to or inhibit acids "eating away" other material.

4. Hydrogen ions are present in acids, but acids remain molecular in solution

That hydrogen ions are responsible for acidic behaviour is relatively well-known, at least among many 16 year old chemists. However, a common model for acid behaviour seems to be that hydrogen ions remain in a molecule and "swap partners" or are "displaced" from this molecule by reaction with an alkali or metal.

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 we "label" as acid or base.

8.3 Suggested activities[8]

1. Introduce acids and bases alongside each other

Rather than allow students to focus mainly on acids, encourage development of knowledge of alkalis too. One common approach is to ask students to test the pH of a range of household substances. Domestic cleaners containing ammonia, toothpaste, "bicarbonate of soda" (used in baking) have alkaline pH values, while fruit juice, vinegar, tomato sauce and shampoos tend to have acidic pH values. This approach needs to be balanced, otherwise children will detect more acids than alkalis. The next step is to test the behaviour of laboratory acids and alkalis to demonstrate that in fact alkalis are more corrosive than acids. This may be done by dropping samples of dilute acid and alkali on to a range of substances such as paper, nylon, aluminium foil and cotton. The samples can be inspected over time. The alkali will cause more corrosion than the acid.

2. Show the difference between "strong" and "weak" and dilute and concentrated

Sequential 1:10 dilutions of a strong acid, strong base, weak acid and weak base will show that pH changes by 1 whole value for every dilution. A strong acid or base will require more

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[8] Some of these activities feature in Barker (2002).

dilutions to reach the same value as a weak base. This suggests that there are more particles responsible for acidity/ alkalinity present in strong acids and bases than in weak ones.

This can be contrasted with concentrated solutions in which a large amount of any substance may be dissolved in water. This is independent of whether the acid/ base is "strong" or "weak", but applies equally to non-acidic substances such as sodium chloride or sugar.

3. *Introduce "neutralisation" as a reaction involving an acid and a base reacting together*

Students can carry out a titration between a strong acid and a strong base, measuring the pH and temperature after the addition of each aliquot of acid. Plotting the results reveals that the highest temperature and the neutral point coincide. Molecular models can be used to reinforce the reaction between the acid and base, showing that water and a salt are formed. In discussion, students can be led towards the notion that formation of bonds in water is a source of the energy. Varying the acid to dibasic and tribasic reveals that more energy is released – this can be directly related to the equations for the reactions.

9 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.

9.1 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 olds revealing 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 this will prevent students from continuing to use incorrect strategies. A third suggestion points to use of problems which stimulate thinking, rather than application of an algorithm. In this study, these authors found this helped to build students’ problem-solving abilities.

9.2 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.

9.3 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.

9.4 Researchers' suggestions for 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.

9.5 Summary of key difficulties

1. Chemists do not agree on how the ”mole” should be defined
Chemists have discussed what is meant by ”one mole” over the last fifty years. The mole has three meanings: an individual unit of mass, a portion of substance and a number. Chemistry teachers frequently adopt the simplistic standpoint of a ”counting unit”, which fits with none of these. Regardless of the experts' philosophical discussions, students need a clear approach based on making the connection between the amount of substance and a numerical quantity.

2. The mole is taught as an abstract mathematical idea
The mole is often taught in a mathematical way causing the chemical meaning to be obscured. Students who struggle to manipulate numbers and symbols will find this approach towards learning the mole very difficult to understand.

3. Students lack secure understanding of preliminary concepts
The mole is an idea which connects basic principles about chemical reactions to the more advanced concepts involving controlling reactions. Thus, prior to learning about the mole, students should understand that chemical reactions produce new substances; that matter is made from tiny particles invisible to the naked eye; and that chemists need to be able to measure amounts of substance accurately in order to be able to control chemical reactions.

4. Avogadro's number cannot be ”seen”
The size of Avogadro's number is too large to be readily comprehended. Students can be given an impression of its size by the use of powerful visual images such as one mole of sand grains stretching for one mile (1.6km); one mole of marbles foming a layer 1500 km deep over the UK and Eire.

9.6 Suggested activities[9]

This is a tried and tested teaching sequence. With patience and care, the mole can be taught to most chemistry students with little difficulty.

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[9] These activities are published in Kind (2004 in press) and Barker (2002).

1. Show students elements in a whole-number mass ratio

Have ready pre-weighed samples of familiar chemical elements and compounds clearly labelled with symbols, formulae and A_r / M_r values. Include two elements with A_r values in a simple whole number ratio – copper (assume A_r = 64) and sulfur (A_r= 32)are good examples.

Start two columns on a board, one for each element, writing the symbol at the top of each and the A_r value then the ratio (2:1) underneath. Ask students to imagine one atom of each element and to state what the ratio of the masses will be (2:1). This is easy! Next ask if it is possible to weigh one atom conventionally. The answer is no. Explain that chemists need to be able to compare masses that can be measured easily.

2. Show that the ratio remains fixed, regardless of the number of atoms

Extend the columns by writing increasingly large numbers of atoms - the number could be written once for both columns, or separately in each. The numbers should go up to 1 000 000. Point out that even one million atoms cannot be measured out conventionally because atoms are just too small. Each time a number is added, refer to the mass ratio – note that this is always the same, 2:1. Reinforce the fact that the ratio is fixed.

3. Introduce the masses in grammes which chemists use: ask about the number of atoms present

Next, refer to the labels on the jars – it is possible to measure out amounts of chemicals, but how have chemists done this? What is special about the amounts? Find the jars for the two chosen elements and write these masses in grammes on the lists. Ask students to state the ratio of the masses – this is unchanged, 2:1. Then comes the crucial question, "What can they say about the numbers of atoms in the two jars?" Wait patiently for the response, repeating the discussion if necessary. Eventually someone will make the connection between the ratio of masses of atoms and the ratio of masses weighed out in the jars, saying that therefore the number of atoms in the jars must be the same.

4. Introduce Avogadro's number, reinforce atom size

When satisfied that this has been understood by most of the group, introduce these points: that atoms are extremely small; the number of atoms present is extremely large; the number of atoms is called Avogadro's number; that we call this number and amount of material "one mole". Reinforce the discussion with visual images of Avogadro's number, such as that one mole of the sweet called "marshmallows" would make a layer 1000 km deep over the entire USA (see also 9.5.4 above).

5. Use formula cards to reinforce the ideas

Make a set of "formula cards" (see Barker 2002 for examples). Each card in the pack will have the symbol and A_r value for one chemical element. Make elements with one "combining power" square-shaped, then double and triple the length for elements with combining powers of 2 and 3. This will enable students to make formulae of simple compounds such as water by aligning two hydrogen cards with one oxygen card, making a two-by-two square, for example. Ensure there are sufficient cards for students to be able to construct the reagents for a chemical reaction. For example, the reaction between hydrogen and oxygen will require four hydrogen cards and two oxygen cards. Use the cards every time students meet a new chemical reaction. Reinforce the notions that new substances are made and that mass is conserved. Encourage students to write chemical equations accurately, based on the formulae they make with the cards. Students can then see easily that the M_r values of elements and compounds are the sums of the A_r values of the component elements and be introduced to the fact that the large numbers in front of formulae represent the number of moles present. These cards are invaluable when working with students of all abilities.

6. Introduce mathematics later

With sufficient practice, students will see the relationship between moles, mass and A_r / M_r values for themselves. When introducing this, ensure that all examples fit simple ratios and use familiar substances. Support learning using chemical reactions which can be demonstrated in front of students, measuring amounts explicitly and showing what happens when excess is used. The reaction between iron and sulfur is a good example. Then, *when and not before* students are secure using formula cards, for example, seeming not to need them for simple reactions and showing signs of memorising the information they contain, take them away. At this point, mathematics can take their place. The embedding process may take weeks, not just a few lessons. If necessary, revisit the original discussion and provide support for students for whom progress is less rapid. Being patient while gradually building students' confidence will pay dividends later.

10 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 falling 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.

10.1 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, “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. Taber and Watts (1996) found this language 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 post-16 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" using 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.

10.2 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 post-16 chemistry course by recognising a class of bonds found between metals and non-metals 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 students beginning post-16 courses 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 indicating 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 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 - one 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 states that bonds can only form between atoms that have donated or accepted electrons. 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.

10.3 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.

10.3.1 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

Barker (1995) and Taber (1993a) have explored students' thinking about hydrogen bonds. In Barker's survey, 250 students beginning post-16 chemistry study 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 learn 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.

10.3.2 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, students starting post-16 chemistry study divided into four groups. Those who thought that covalent substances have lower boiling points, so more heat was needed to vapourise the magnesium chloride numbered 22%. About 13% thought that ionic bonds can't be broken by heating. Almost one-quarter (24%) suggested that covalent bonds are weaker than ionic bonds so break. About one-third (33%) gave no response or an uncodeable response. 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).

10.4 Summary of key difficulties

1. Compounds with ionic bonds behave as simple molecules

Students see the formulae of ionic bonds written as "NaCl" or "$MgCl_2$". There is no distinction between these formulae and "CH_4" or "H_2O", which are mainly covalent compounds. The three-dimensional structure of compounds with mainly ionic bonding is ignored. Although this is chemical convention, students learning chemistry need help to realise that compounds with mainly ionic bonds behave differently from those with covalent bonds. For example, understanding that ions separate when a mainly ionic compound dissolves in a solvent, rather than the "molecule" staying together.

2. The central (first) element in a formula is responsible for bond formation

The convention for writing formulae contributes to the misconception that the first element in the formula is the more "powerful". In methane, for example, carbon is perceived as "needing" four bonds, while hydrogen is the weaker partner with each "needing" only one bond.

3. Atoms "want" to form bonds

An extension of the idea that atoms "need" to form bonds is that atoms make decisions about making bonds. This reasoning may come from analogies such as "holding hands" or "finding a partner" used in teaching. This strategy causes problems later when students attempt to learn the role of energetics in bond formation.

4. There are only two types of bond – covalent and ionic

Pre-16 teaching focuses almost entirely on covalent and ionic bonds to the extent that students think that all bonds must be "ionic" or "covalent". As the vast majority of chemical bonds fall between these two extremes or are intermolecular, this is unhelpful.

5. Covalent bonds are weaker than ionic bonds

Teaching presents differences between "covalent" and "ionic" compounds in terms of melting points, boiling points and physical states. Simplistic explanations ignore the role of intermolecular bonds, leading students towards, for example, poor models for explaining changes of state.

10.5 Suggested activities[10]

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[10] These are published in Kind (2003) and Barker (2002).

1. Explore students' understanding of simple events

Water boiling, sodium chloride and sugar dissolving, ice melting, iodine subliming and propanone evaporating can all be used to investigate students' thinking about chemical bonding. Make the events explicit by carrying them out in the students' presence and using molecular models to probe thinking about which bonds break and form.

2. Use cognitive conflict to show why elements form different types of bond

Show students that bonding depends on atoms forming compounds in the most energetically favourable way. Make three grids with 2, 8, and 8 boxes in each, aligned as if to represent electrons. Make the boxes big enough so that a mini-chocolate bar will sit inside. To start, use eleven chocolates in one grid arranged in a 2.8.1 formation, representing the electrons in one atom of sodium and seventeen chocolates in a second grid arranged in a 2.8.7 formation to represent the electrons in one atom of chlorine. Say that when compounds are made, all the electron spaces are usually filled. How might sodium and chlorine atoms arrange electrons so all the spaces are filled? Invite a student to move the lone chocolate from the "sodium atom" to the "chlorine atom". To earn a chocolate, a student must then reason what would happen if magnesium replaced sodium? This time, make a "magnesium atom" by placing twelve chocolates in a 2.8.2 arrangement in the grid used for sodium, but keep chlorine the same. Ask the same question as before – how might magnesium and chlorine atoms arrange electrons so all the spaces are filled? Students will avoid the chemist's answer, saying for example that an extra space is created or that the extra electron is "lost". Eventually someone will realise that an extra atom of chlorine is needed. At this point bring out the third grid, showing that the unit formula for magnesium chloride is $MgCl_2$. The discussion can then be extended to show how different ways of filling the electron spaces can be used, depending on the most energetically favourable situation. Electron transfer may be preferred in some reactions, while electron sharing is used to form other compounds.

Extension further allows discussion of physical states of common compounds such as methane, water and sodium chloride. These three can be used to introduce covalent, ionic and polar covalent bonds, with the additional idea that in practice most compounds fall between the extremes of ionic and covalent bond types.

3. Use electrostatics to explain bond formation

Describe the particles involved in chemical bond formation, stating always which is negatively and which positively charged. For example, electrons in a covalent bond are negatively charged and the bond forms between electrons and positively charged nuclei. An ionic bond comprises positively and negatively charged ions attracting each other in a three-dimensional arrangement. An intermolecular bond forms between the positive charge region on one molecule and negative charge region on another. Using this type of language helps students to focus on the particles involved in chemical bonding, rather than the bulk properties of the compounds. This approach is helpful to students making a transition towards electron orbital interactions which are used at university level to explain these ideas.

4. Be consistent in using "bonding" terminology

A range of different terms is used to describe bonds in English, particularly intermolecular bonds. These include "van der Waals forces", "London forces", "attractive forces" and "attractions". There is no need for this. Such language over-complicates the picture. Terms such as "induced dipole-dipole bonds" and "permanent dipole- permanent dipole bonds" are much more descriptive, as these explain clearly the kind of interaction involved. Students can then work out (or use the term because they have already worked out) the particles involved in making these bonds, rather than be left with a memory exercise. Also, this language means that consistency can be introduced in discussing relative bond energies – chemists do not talk about "relative attractive force" energies! Using language which supports energetics teaching is helpful to students developing correct thinking.

5. And two things to avoid

Teachers working with pre-16 year olds tend to over-rely on the "octet rule" as an infallible tool for students to use in determining formulae and bonding. This contributes 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". 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. This is even before the inert gas compounds are considered.

Use of anthropomorphic analogies to explain how bonds form should also be avoided. These only give students false ideas about atoms "wanting" to form bonds, or "needing" a certain number of bonds, or "finding a partner". The analogy is patronising – far better to make students think about the chemical elements as chemicals than "living" organisms.

11 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.

11.1 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 that 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.

11.2 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).

11.3 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 the energy seems to have 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.

11.4 Summary of key difficulties

1. Fuels are energy "stores"

This idea is common, even among post-16 students. Sensory perception leads students to this idea, because the oxygen involved in a combustion reaction is invisible. Also, in teaching about fuels and food reference is often made to fuels "containing" energy, or food "giving" energy without reference to the chemical reactions involved. The idea contributes to students finding calculation of energy changes in reactions problematic.

2. Energy can be created and used up

Allied to the above is the idea that energy can be created and used up. Energy appears to be created from a burning reaction. Energy "runs out" when a fuel supply is exhausted; a non-rechargeable battery will also "run out" of energy eventually. The language we use to describe these events leads students to the perception that energy is like a substance that can be made and used up. This prohibits their learning that energy is conserved and dissipated when released in chemical reactions.

3. Energy is released when chemical bonds break

Taking the idea that fuels are energy "stores" further leads students learning about chemical bonds to think that bond breaking releases energy. This is similar to thinking that cracking an egg releases the egg's contents. Some students will also reason that although some energy is needed to break a bond, more is released when it is broken.

11.5 Suggested activities[11]

1. Improve students' understanding of energy conservation

Boohan and Ogborn (1996) developed a useful "picture language" representing a wide

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[11] Some of these activities are published in Barker (2002).

range of energy changes. This can be used to introduce key ideas about energy transfer including that energy is conserved and never destroyed. The language can be used with 11-16 year olds as it stands, but some modification is needed to develop chemical situations. The principle must be to encourage students to think of energy as being available in "useful" and "non-useful" forms. As such, a fuel-oxygen system may be described as a "useful" form of energy because the energy can be transferred to do "work" in some way.

2. Use consistent language referring to "fuel-oxygen systems"

In teaching about energy we must refer to "X-oxygen systems" not just "X" – where this may represent a fuel or other reactant. This will help to prevent students thinking that just the fuel or other chemical is an energy "source". By doing this, students can be led towards the understanding that chemical bonds are involved in "storing" and "releasing" energy.

3. Introduce entropy at an early stage

Introducing entropy early on will help students to understand how energy is conserved and why we can use some forms of energy and not others. Spread out energy is "non-useful", although the amount of energy present in any change is constant.

The qualitative ideas associated with entropy are not difficult and make a lot of sense when coupled with energy conservation. An 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. This can be related to every day events, such as winning the big prize in a national lottery, a certain football team winning the major league, the sun rising tomorrow, and so on. Students can be invited to think of the "odds" of the most likely event happening. For example, the odds on winning the UK national lottery big prize are approximately 14 million:1, so the most likely event on buying a ticket is that the buyer will not win! Similar reasoning can be applied to chemical events – for example, the odds on two chemicals mixing is very high if both have similar types of molecule. There is only one possible arrangement that ethanol and water could be completely separated if the two liquids are poured into one container, but many ways these could be mixed. The prediction would therefore be that the chemicals would mix. The message students need is that the most likely event to happen in real life is the one with the most possibilities that it can occur. For energy, the most likely event is that energy will spread out, not stay in one place. Therefore this is what is most likely to happen.

4. Use molecular models to improve understanding about chemical bonds

Students need help to focus on energy being required to break chemical bonds. One approach 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. To maximise the benefit from this experiment, related fuels, such as the alcohols, should be used, 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 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.

We also 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.

12 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 preuniversity 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.

12.1 Issues in learning about chemical equilibria

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.

2. An equilibrium reaction involves two separate reactions

Experienced chemists consider the forward and reverse reactions part of the same chemical system. Students 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 have 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.

Additional evidence for this reasoning comes from several other workers. Gorodetsky and Gussarsky (1986) found this in one-third of 17-18 year old chemists. Cachapuz and Maskill (1989) used word association tests (WATs) with 14-15 year olds to reveal the same thinking. Banks (1997) tracked the developing understanding of a small group of post-16 chemists through a post-16 chemistry course and found further evidence.

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 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.

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.

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 and 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.

12.2 Summary of key difficulties

1. Equilibria are static, not dynamic

Students mainly experience chemical reactions that appear to go to completion. When they meet a reaction which does not go to completion, but which has a reverse reaction occurring to a significant extent, it is unsurprising they think of the equilibrium position as being fixed. That is, once achieved, there is no movement of particles between the two "sides". This is a version of the reaction being complete.

2. An equilibrium reaction comprises two separate reactions

Perhaps the next step for students in learning about equilibria is to recognise that two reactions are occurring, but to think of these as separate from each other. Research suggests that using the double-headed arrow may contribute to this.

3. Le Chatelier's Principle is used as if it applies in every case

Le Chatelier's Principle is taught widely in post-16 chemistry courses as it has gained a reputation as a useful tool for predicting changes to an equilibrium position under some circumstances. However, students who are taught this as the only strategy for considering how an equilibrium position is adjusted will not learn that this Principle does not always apply.

4. Rate and equilibria can be confused

There is some evidence suggesting that students perceive the rates of one reaction in an equilibrium system may alter, while another slows or remains constant. They have not grasped the notion that rate applies to the system as a whole, rather than the component reactions. This difficulty is related to students' perception of two separate reactions.

12.3 Suggested activities

1. Present a wider range of reactions to 11-16 year olds

Students need to experience a wider range of reactions than is demonstrated currently. We should not be afraid of showing situations which do not meet an 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 equilibria in a qualitative way.

2. Teach using equilibrium laws and the laws of van't Hoff

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, use of the Equilibrium Law may be added. LCP is unnecessary and unhelpful. However, consider 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.

3. Use diagnostic tests to determine students' understandings

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 are likely to be useful in determining students' starting points, their progress and change in thinking post-teaching.

13 Discussion

Here several issues are discussed: 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.

1. Going "Beyond Appearances"

The report is entitled "Beyond Appearances" because that is how chemists approach the world: in terms of the unseen particles making 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.

2. Develop sound and consistent pre-16 chemistry teaching

A number of references have been made to pre-16 teaching strategies on chemical learning. Two major points can be made. First, 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. Hence, many of the comments about how we teach these topics in pre-16 courses apply to us all. I also taught lessons involving students compiling a table comparing the boiling points and structures of covalent and ionic compounds and teaching ionic bonds in potentially unhelpful ways. However, second, 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.

3. Developing mathematical skills

Chemical concepts seem to divide neatly into those referred to as "qualitative" and "quantitative". "Qualitative" concepts are those which do not require additional skills from outside the subject, particularly mathematics. In this category are particle theory, changes of state, chemical change, (including acids and bases and elements, compounds and mixtures) and chemical bonding. These can be taught without mathematical skills. "Quantitative" concepts use higher order maths skills such as proportion and ratios, logarithms and probability. Besides teaching the basic qualitative concepts well, students also need the necessary skills from outside chemistry to cope with the extra demands made by the quantitative areas.

4. Possible future research

This report reveals that certain concept areas have received extensive treatment from researchers, while others are relatively unexplored 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. We can do much more to share these, develop them and help new teachers learn them. Thirdly, further work on developing diagnostic tests to help determine student progress in learning would be useful. 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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