An evidence-based approach to introductory chemistry

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ABSTRACT Drawing on research into students' understanding, this article argues that the customary approach to introductory chemistry has created difficulties for students. Instead of being based on the notion of 'solids, liquids and gases', introductory chemistry should be structured to develop the concept of a substance. The concept of a substance is defined and how the absence of this concept causes difficulties is explained. Important developments in the new National Curriculum in England are highlighted and taken further to show a curriculum structured around the concept of a substance.

Students' misconceptions in chemistry are well documented (for example, Barker (2002)). This article argues that there has been a fundamental problem with the introduction to chemistry in successive versions of the National Curriculum in England (and before) which has disadvantaged students. The introductory curriculum (up to the end of key stage 3, age 13–14) fails to give proper attention to the central concept of chemistry; namely, the concept of a substance. In consequence, the scientific coherence of the curriculum is questionable and the learning needs of students are not being met. This strong and perhaps controversial viewpoint is based on evidence from research into students' understanding. I will outline the chemist's meaning for 'a substance' and the uninitiated student understanding. These two perspectives then inform an analysis identifying shortcomings in the customary curriculum. Findings from a recent large-scale study are given in support of the argument. Looking forward, the article notes important changes in the new National Curriculum that begin to give due recognition to the concept of a substance and shows how, taken further, the curriculum could be restructured around this central concept.

The chemist's concept of a substance

A substance is a unique kind of stuff, identified by certain invariant properties. These properties do not depend on the shape/design or size/amount of the sample of the stuff; that is, they do not depend on the 'object' made of the stuff. Substances can be involved in three distinct kinds of phenomena:

- a substance can mix with one or more other substances to produce a mixture of substances (conversely, mixtures can be separated);
- a substance can change state; setting the possibility of decomposition aside, depending on the conditions, a substance can exist in each of the three states;
- in interaction with other substances, or alone, substances can cease to exist, with new substances created in their place; in other words, they can undergo chemical change.

Figure 1 gives a concept map setting out these propositions, which together define the concept of a substance at a descriptive, macroscopic level. This way of seeing is explained by particle theory.

A 'basic' particle model can deal with mixing and changes of state. The phenomena are explained by changes in the movement and arrangement of these particles. A deeper level of detail (involving atoms) is needed to explain chemical change. Without going into details of atomic structure and kinds of bonding (covalent, ionic, metallic), a substance can be defined in terms of how atoms are bonded together. Here, two types of structure are possible: molecular structures and giant structures (see Figure 2). For molecular structures, the substance is defined by which and how many atoms make up a molecule. This corresponds to the formula of the substance. At advanced levels, the precise arrangement

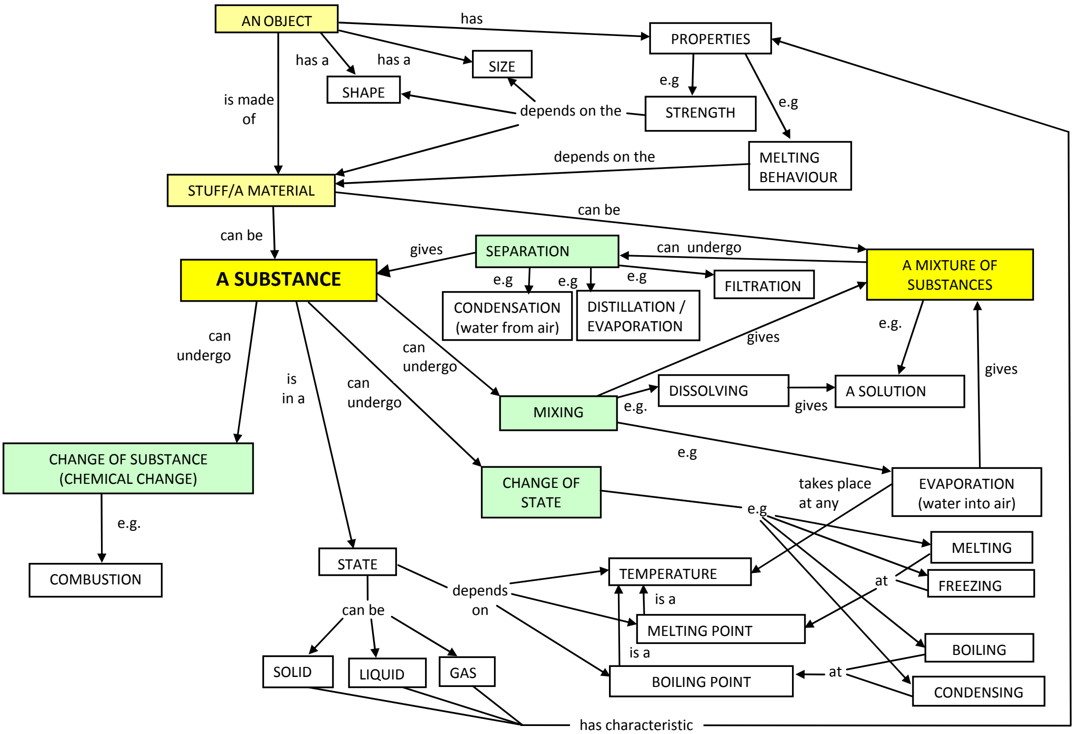


Figure 1 The concept of a substance; from Johnson and Papageorgiou (2010)

becomes important in recognising structural and geometric isomers. For giant structures, the ratio of the atoms (the repeating unit) corresponds to the formula of the substance. It is important to appreciate that the observable properties of a substance result from how atoms are bonded together and not their individual nature. This is well illustrated with pairs such as oxygen (O_2) and ozone (O_3), and diamond and graphite, where different bonding arrangements with the one type of atom give very different properties.

The possibility of chemical change is explained by a change in the bonding between atoms. Clear-cut examples involve atoms re-bonding with different types of atom. Some changes are more ambiguous, such as grey tin to white tin. Is this a chemical change (the two have very different properties) or a phase change? Opinions aside, the task of chemistry education is to enable students to join such a debate.

The uninitiated student perspective

Details of the research evidence from the literature informing the portrayal of the student perspective that is discussed in this section can be found through Barker (2002) and Johnson and Tymms (2011). Instinctively, students do not hold the concept of a substance. They do appreciate that different kinds of stuff can mix up to make mixtures, but there is no distinction between starting ingredients that are substances or mixtures of substances. So, uncooked cake is recognised as a mixture, but there is no differentiation between sugar (sucrose) and flour as types of stuff. By and large, students can recognise what is ‘solid’ and what is ‘liquid’, but their perception of the gas state is very vague. They have little sense that ‘gases’ are stuff in the same way that, say, iron and water are stuff. Without the concept of a substance, the possibility of chemical change is inconceivable to them. They cannot recognise chemical change let alone understand how such a thing can happen.

Phenomena that chemists see as chemical change students interpret in different ways. For example, even though iron and rust look very different, there is no conceptual framework that allows students to think they could be two different substances. Some will say that rust is still iron, but in a different form. Others will say that

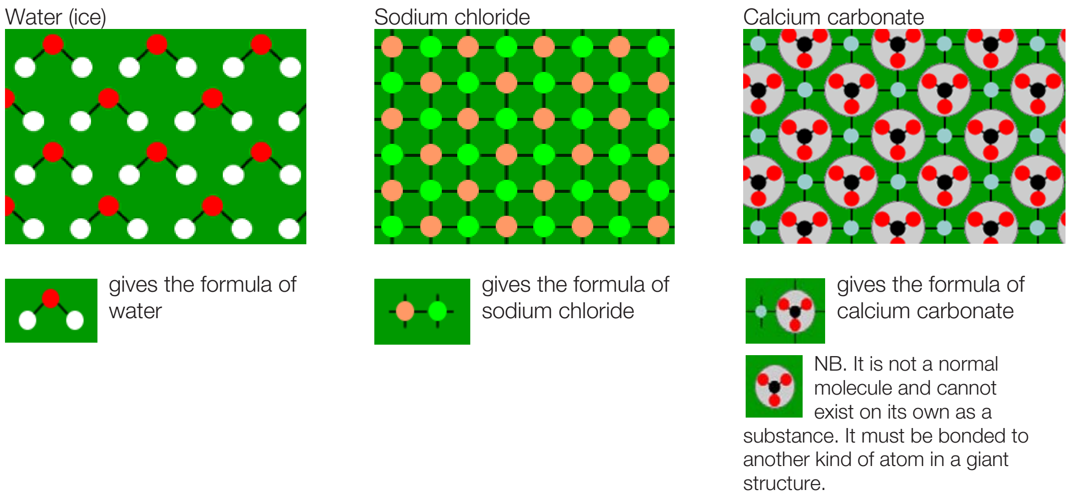


Figure 2 Some bonding structures; from John and Roberts (2006)

rust is a mixture of iron and something else; that is, two substances.

The concept of a substance that allows for the possibility of the gas state and for substances to change into other substances is not at all self-evident.

The customary chemistry curriculum

Although relevant content is addressed, the concept of a substance is missing from the customary introduction to chemistry. Thus, in the early stages there is no distinction between named materials that are mixtures of substances and those that are single substances. There might be examples where mixtures are separated but the question of how we know whether the separate ingredients are substances is not considered. Melting behaviour is not used to establish the difference between a substance and a mixture of substances (for example, the contrast between water (ice) and chocolate).

Instead, the approach is founded on the notion of 'solids, liquids and gases'. Much attention is given to classifying samples (under room conditions) into these supposed groups. Moreover, the problematic nature of some samples (such as gels and pastes) cannot be dealt with satisfactorily because they have not been recognised as mixtures. Unfortunately, students can come to think that 'solids', 'liquids' and 'gases' are three different kinds of stuff, which is a view reinforced by language that talks of 'a solid', 'a liquid' and 'a gas'. As a different species, 'gases' lose none of their mystery. Scientifically, there are no such things as 'solids', 'liquids' and 'gases' – there are just substances and their three possible states and a variety of mixtures (where assigning a state is not necessarily appropriate).

Instances of samples changing between 'solid' and 'liquid' and others between 'liquid' and 'gas' are included. However, there is little to make students think these are not just a few examples of anomalous behaviour. Water is usually the only example of a substance featuring in all three states and here the gas state is dealt with unsatisfactorily. Through failing to recognise the difference between a pure sample and a mixture, boiling and evaporation below boiling point into the air are both said to be a change to 'gas'. However, a pure sample of water in the gas state requires a temperature of at least 100 °C (at atmospheric pressure); for example, the bubbles of boiling water. A mixture of water and air can exist over a very wide range of temperatures. To say that water changes to 'gas' under such very different conditions is confusing for students. Water changes to the gas state on boiling. On evaporation below boiling point, water is mixing up with the air (vapour pressure can wait for later). There is a parallel with dissolving. When salt dissolves in water we do not say it has melted to 'liquid'. The confusion is often increased when visible mist from a kettle (clouds of condensed water droplets) is erroneously equated to 'gas'. A sample in the gas state is transparent.

Without the concept of a substance, chemical change cannot be addressed directly for what it is. Logic dictates that one needs to know what a substance is before one can recognise a change of substance. Indirectly, the customary curriculum makes a distinction between reversible and irreversible changes, where irreversibility is used as a proxy to mark out changes that are chemical. There can be mention of new materials, but students cannot understand these as new substances. Chemical changes can be both reversible and irreversible and the scientific value of the criterion is very questionable.

Introducing ideas of elements and compounds at key stage 3 without the concept of a substance as an anchor can lead to confusion. Rather than seeing elements and compounds equally as substances, compounds are thought of as mixtures and elements as 'pure'. The widespread use of the term 'pure substance' does not help. Scientifically, 'pure substance' refers to the purity of a *sample* of stuff – whether the sample is one substance or a mix of two or more substances – not to the idea of *a substance*. A substance is a substance. Unfortunately, students can take 'pure substance' literally, thinking it to mean that some substances are pure (i.e. elements) and some are not pure (i.e. compounds).

Particle theory is introduced within the 'solids, liquids and gases' framework and this might well inhibit the development of students' understanding (Johnson and Papageorgiou, 2010). At the basic level, particles are linked to the generic states rather than specific substances. Inadvertently, this could encourage the misconception of particles having the observable macroscopic character: wouldn't there be three kinds of particle for three kinds of stuff: 'solid' particles for 'solids', 'liquid' particles for 'liquids' and 'gas' particles for 'gases'? From this perspective, the strength of the forces between particles is seen as a consequence of kind. So the forces for a solid are strong because the stuff is 'a solid', weaker for a liquid because the stuff is 'a liquid' and very weak for a gas because the stuff is 'a gas'. In this sense, the particle theory has not explained anything. Scientifically, simply linking the relative strengths of force to the room temperature generic state is problematic. Oxygen in the solid state does not have stronger forces than iron in the liquid state.

What the students need is a particle model that explains why different substances have different melting and boiling points and hence coexist in different states at room temperature (scientifically, an arbitrary temperature, but important in relation to our direct experience). Here, a particle having a 'holding ability' linked to the substance identity (which ranges in a continuum from very strong to very weak across different substances) and energy of movement (which depends on the temperature) are the key ideas (leaving aside external pressure). The state of a sample of a substance depends on the balance between its particles' 'holding ability' for each other, and their energy.

Ideas of structures are addressed along with atomic structure and different kinds of bonding at key stage 4 (ages 14–16). Therefore, when atoms are first introduced (at key stage 3), the distinction between the atom and the substance is not emphasised. This can cause confusion, especially since the same name is used for the atom and the first discovered substance made from that one type of atom. The statement that 'water is made of hydrogen and oxygen' is open to different interpretations. For the chemist, in this context hydrogen and oxygen refer to atoms and water is one substance. If hydrogen and oxygen are taken to mean the substances hydrogen and oxygen, this says there are two substances in water, confirming the notion that compounds are mixtures.

Evidence from a recent large-scale study

Figure 3 gives results relating to aspects of melting behaviour from a wider study on the concept of a substance, involving 4700 key stage 3 students from 31 schools across England (Johnson and Tymms, 2011). The study used fixed-response items and the data were analysed by Rasch modelling (Bond and Fox, 2007). Rasch modelling produces a chart where items and students are placed on the same interval scale. Here, the scale presumes to measure 'understanding of the concept of a substance'. For items, the scale gives the 'difficulty'. For students, the scale gives the 'ability'. For a subsample, data on general academic ability were also available from Durham University's Centre for Evaluation and Monitoring (www.cem.org/midyis), which enables an estimate of the national picture. The subsample of about 1000 students in each of years 7, 8 and 9 sat the tests at the end of the 2007 academic year. The estimate suggests the average student is around 42 on the scale of Figure 3 by the end of year 7, moving up to around 46 by the end of year 9 (with standard deviations of about 8).

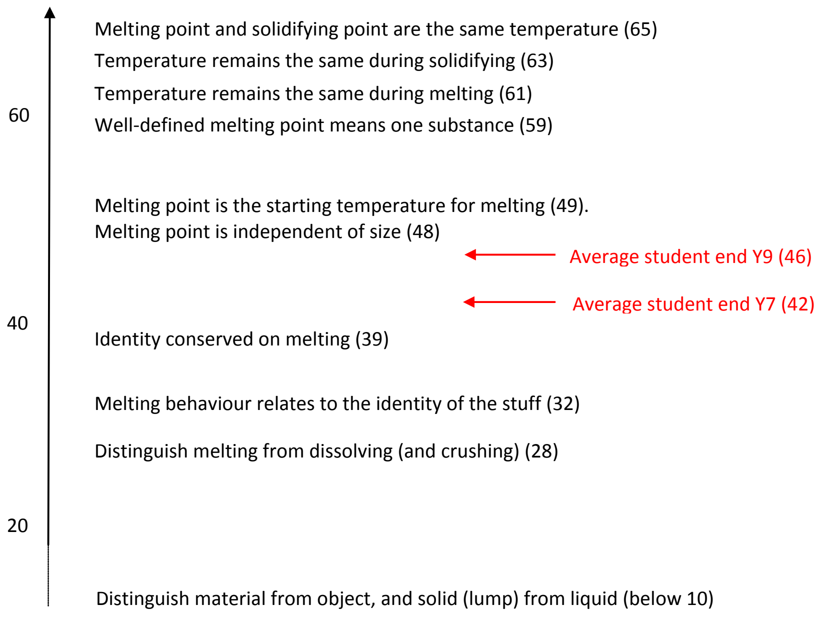
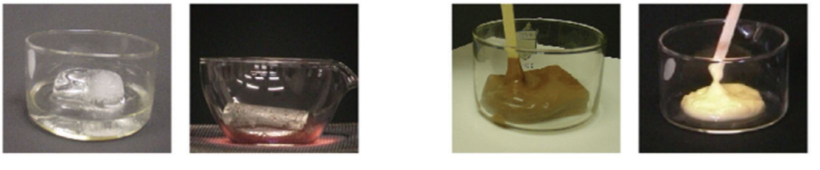


Figure 3 Relative difficulties of items related to melting

To give some flavour of the tests, Figure 4 presents an item assessing the idea of melting behaviour indicating the purity of a sample of stuff. Its high scale position (59) probably reflects lack of curricular attention rather than inherent difficulty. The most popular distractor was option D – 'No. It just tells you some things melt differently.'

Some materials melt sharply - they go straight from solid to a runny liquid. For example, water (ice) and lead:

Others, like chocolate and butter don't melt clearly - they go through a gooey stage:



Does this difference in melting behaviour tell us anything about the material?

- [ ] Yes. Melting sharply means it is one substance.
- [ ] Yes. Melting sharply means it is a mixture of substances.
- [ ] Yes. Man-made materials don't melt sharply.
- [ ] No. It just tells you some things melt differently.
- [ ] No. You need to know where it comes from.

Figure 4 Melting behaviour item

Boiling behaviour was also explored and forms a similar sequence to melting. Alongside students' developing understanding of changes of state, that a substance can exist in each of the three states falls in the region 56–63 across various substances.

The study included 19 items addressing assorted examples of chemical change and these fall in the region 67–82. Here, the focus was on how students viewed the products of a reaction in relation to the reactants. Were the products understood to be new substances with their own identity? Recall of reactions and the names of substances were not required. In most cases, the item included a video showing the reaction taking place. Otherwise, photographs were used. For example, students were shown a video of the reaction between calcium and a little water in a test tube. To start with, the tube is at an angle with a few lumps of calcium resting above the water. On moving to a vertical orientation, the calcium slides into the water and the reaction causes a plastic bag attached to the mouth of the tube to inflate and the creation of white powder in the tube. Two questions followed – one about the white powder and one about the contents of the bag. The options for the white powder were:

A Calcium in a different form;
B A mixture of calcium and water;
C What is left after a gas escapes from calcium;
D A new substance that isn't calcium or water.

The most popular option was B, followed by A then C, with fewest choosing the correct answer, D (difficulty 71). That the bag contained a new substance is more difficult at 73.

Items also addressed students' understanding of particle theory. Without going into details of the preceding progression, understanding that the particles do not carry the observed macroscopic properties comes in the region 60–63 for all three states. That there is empty space between the particles is more difficult at 65–69.

One must accept that the difficulty of any item might reflect factors other than the difficulty of the target idea, and the values in Figure 3 have some latitude. Nevertheless, even allowing a wide margin of error, the study suggests that by the end of key stage 3 most students have hardly begun to develop the concept of a substance, the very concept that is so central to understanding chemistry. However, since the customary curriculum overlooks this concept, the students' difficulties are not surprising. What about the new National Curriculum?

Chemistry in the new National Curriculum

In the new National Curriculum in England there is no specific mention of the concept of a substance throughout primary level and thus no distinction between substances and mixtures of substances in named materials. The terms 'material' and 'substance' are interchanged in places without differentiation in meaning. At lower key stage 2 (ages 7–9), under the heading of 'States of Matter', materials are still to be grouped as either 'solids', 'liquids' or 'gases'. However, students are to be taught about the temperatures at which 'some materials change state'. That some materials do change state at a well-defined temperature (which can be recognised by the sharp change from solid to liquid as in Figure 4) invites the introduction of the concept of a substance, but it is not clear whether this is intended. The damaging misconception of three types of matter could be countered. 'Solids' should be read as 'the solid state' and so on, which better fits the section heading. The examples of iron melting and oxygen condensing appear in the non-statutory guidance. It would be good to extend these to iron boiling and oxygen solidifying (freezing).

At key stage 1 (ages 5–7), the non-statutory guidance could be clearer in the distinction between the object and the material with respect to properties. For example, rough/smooth relates to the design/shape of an object and not the material as such. Bendy/not bendy depends on the design/shape and amount/size as well as the material.

The criterion of reversibility still appears in upper key stage 2 (ages 9–11), though making new materials (chemical change) is described as 'not usually reversible' rather than as 'irreversible'. This is scientifically more accurate but is not likely to be helpful to students. It would be better to emphasise that, for changes of state and mixing, the same substances are still there, but to note that there is another kind of change where the substances change to different substances (which cannot be explained until key stage 3).

At key stage 3, the concept of a substance does appear but in a section headed 'Pure and impure substances'. The heading is unfortunate. As noted earlier, the term 'pure substance' is misleading and a distinction must be made between 'a substance' (which cannot be pure or impure) and a sample of material which can be pure (just one substance) or impure (a mixture of more than one substance). Taking 'pure substance' to mean 'a substance', its inclusion is encouraging. However, the presentation of the curriculum does not portray the central importance of the concept. The various section headings do not give due attention to contingency and progression. Fundamentally, I would argue that the curriculum ought to be structured around the concept of a substance, explicitly. How would this look at key stage 3?

The key stage 3 curriculum structured around the concept of a substance

Box 1 presents a progression to develop a fundamental understanding of the concept of a substance (Figure 1) that integrates a developing particle model.

Although it is covered at key stage 2, many students are likely to be unsure about the gas state. The recommendation to use the particle

BOX 1 A curriculum to develop the concept of a substance at key stage 3

Substances and states

- A sample of a substance has a well-defined melting point
- Melting point/freezing point is a switching temperature between the solid and liquid states
- A basic particle model to explain the change between the solid and liquid states and different melting points.
- Using the particle model to predict the gas state
- Boiling point/condensing point is a switching temperature between the liquid and gas states
- Using melting and boiling points to predict the state of a substance at room temperature and other temperatures
- The particles do not change, so there is no change in mass during a change of state

Mixtures of substances

- Melting/freezing and boiling/condensing behaviour to distinguish between a pure sample of a substance and a mixture of substances.
- Air as a mixture of substances
- Water below boiling point mixing into the air (evaporation)
- A distribution of energy among particles to explain evaporation below boiling point
- The presence of water in (clear) air and its condensation on cooling the mixture; the temperature at which condensation forms depends on the concentration of water in the air
- Dissolving (for solutes where pure samples are in the solid, liquid and gas states)
- A basic particle explanation for dissolving; there is no change in mass since the particles do not change
- The range of solubility of different substances in water from extremely low (in effect insoluble) to extremely high (completely miscible)
- Mixtures that are not solutions: suspensions, pastes, gels, emulsions, foams and mists
- Separating mixtures: filtration, evaporation, distillation and chromatography

Substances and atoms

- Substances being made of bonded atoms
- Giant and molecular as two types of bonding structures and the link between structure and melting point
- Elementary substances (one type of atom) and compound substances (two or more types of atom)
- Chemical symbols for atoms and formulae for substances (the atoms in a molecule or repeating unit of a giant structure)

Substances changing into other substances

- Using bonding structures to predict the possibility of substances changing into other substances through the rearrangement of atoms; there is no change in mass since the number and type of atoms does not change
- Chemical reaction on mixing substances at room temperature (e.g. calcium and water)
- Chemical reaction on heating a mix of substances to a higher temperature (e.g. magnesium and oxygen)
- Chemical reaction on mixing substances in solution (e.g. lead nitrate and potassium iodide)
- Chemical reactions needing the presence of a catalyst
- Representing chemical reactions by word equations, bonding structure diagrams and formula equations
- Decomposition of a substance on heating (e.g. copper carbonate); not all substances have melting and boiling points
- Using chemical reactions to identify a substance (e.g. carbon dioxide with limewater)
- Exothermic and endothermic chemical reactions (qualitative)

theory to predict the gas state derives from a longitudinal study (Johnson, 2005) which suggested that students needed an explanation of how the gas state was possible before they could believe 'gases' were substances. Similarly, the longitudinal study suggested that ideas of atoms and bonding structures played a significant role in students' acceptance of chemical change. An explanation of the possibility of chemical change was necessary before students were willing to believe substances could cease to exist, with new ones created instead.

There are advantages in separating the idea of bonding structures (see Figure 2) from atomic structure and types of bonding at key stage 4. The two kinds of bonding structure explain the wide range of melting and boiling points students will have met. There is a natural progression from representing a chemical change with bonding structure diagrams to formulae and balanced equations. Establishing the idea of giant structures before types of bonding ought to help counter misconceived molecular interpretation of ionic bonding (Taber, 2012). Since chemical change is such a strange notion to students, attention is given to its occurrence under different conditions.

The conservation of mass is included in Box 1 but this is somewhat surplus to particle accounts of phenomena. Students' difficulties are not related to the conservation of particles but to how their mass exerts a weight. Understanding how a sample in the gas state exerts weight through a pressure gradient is not so simple. Students with the misconception that floating objects have no weight can think particles in a solution lose weight. These issues are more in the realm of physics.

To explain evaporation below boiling point, the basic particle model is refined to include the idea of a distribution of energies among particles at a temperature. A simplified notion of high, medium and low energy particles will suffice (Johnson, 2012). Students do need to be able to reconcile boiling with evaporation below boiling point.

Consideration of the energy changes and temperature–time graphs for changes of state has not been included in Box 1 since these are challenging ideas for early on and not essential to the later developments. Of course, with more able students, changes of state could be given the full treatment in one go.

The remaining content in the new specification can be treated as relatively independent topic areas, drawing on and consolidating the ideas developed in Box 1. These topics will take on a different feel compared with the customary approach. For the periodic table, it will be important to emphasise the distinction between the atom and the elementary substance. Whether the term 'element' is referring to an atom or a substance must always be clarified. For a topic on acids it should be noted that substances known as 'acids' only behave like acids when dissolved in water. The laboratory bottles of acids are solutions not 'liquids'. Pure samples of these substances can be in either the solid, liquid or gas states at room temperature (for example citric, ethanoic and hydrochloric (hydrogen chloride)). What is observed in the reactions of acid solutions depends on the solubilities of the other reactant and products, and the state of any practically insoluble product that separates out (for example, bubbles of hydrogen).

Conclusion

If one accepts that the concept of a substance is pivotal to understanding chemistry and that students do not hold the concept, it makes sense to structure the curriculum to develop the concept. This article has indicated how the new National Curriculum can be restructured to put the concept of a substance centre stage. A much fuller account is given by *Stuff and Substance* teaching materials published by the Science Enhancement Programme (SEP). Johnson (2011) picks out key milestones along the way to understanding chemical change as a change of substance. Johnson and Roberts (2006) is a multimedia resource that illustrates a substance-based approach to chemistry in detail, from melting to combustion and the reactions of acids. Both publications are available free of charge from the National STEM Centre elibrary (stem.org.uk/rx5fd). Many of the evidence of learning items in *York Science* (Whitehouse, 2013) are derived from the items used in the large-scale research study.

Students' performance under the customary curriculum does not necessarily tell us what they could achieve. Given a more appropriate introductory chemistry curriculum, there is good reason to have high expectations of our students.

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