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Teaching and learning chemistry

Keith S. Taber

This chapter is about teaching chemistry as a science subject, and teaching chemistry topics within more general science courses. Given the very real differences in scientific practices across different disciplines, a school science that does not reflect the major disciplinary differences offers a poor reflection of the diversity within the sciences (Jenkins, 2007). Teaching chemistry has much in common with teaching other science subjects, but chemistry education is also recognised as a field of research and scholarship in its own right - having its own specific journals and conferences. There is a great deal of specific advice that could be given on teaching chemistry topics in secondary school and much of this can be found in the recommended readings at the end of the chapter. The present chapter seeks to highlight some of the key issues and challenges fundamental to teaching the subject. In particular, the chapter will use one commonly met chemical reaction (the combustion of methane) as an example to discuss some of the complexity of core chemical ideas when first met by learners.

The nature of chemistry as a science

Chemistry is sometimes referred to as the central science because it can be considered to be 'between' biology and physics in terms of its subject matter. Actually there is considerable overlap between chemistry and its disciplinary neighbours. Organic chemistry has strong links with biology through sciences such as biochemistry and pharmacology. Some topics studied in physical chemistry are also studied in physics (where they are collectively referred to as chemical physics). Chemistry also informs sciences such as geology, where there is again a linked specialised subject of geochemistry, and the interdisciplinary area of environmental science. Chemistry is then a broad subject with much variety. Whilst the traditional division at upper secondary and tertiary level into

inorganic, organic and physical chemistry is no longer as widely followed as it once was, the study of chemistry involves topics of diverse nature, and requires a wide range of skills. Chemists may specialise in such different areas as organic synthesis, inorganic quantitative analysis, statistical thermodynamics, or quantum chemistry - and school chemistry needs to offer a flavour of this range.

The challenge of the subject matter of chemistry

Chemistry as a science is the study of substances and their properties, and especially their interactions with each other. This simple statement belies one of the challenges of teaching and learning chemistry in that it is concerned with substances, but the idea of a substance (in the scientific sense) is not something familiar to students from the use of the word in everyday discourse. What are familiar from everyday experience are materials, such as steel, wood, various plastics and the like, and mixtures such as orange juice and air. Some common materials are in effect substances (ice and some plastics would be examples) but conceptually 'substance' is a very special category of things, distinct from 'material'. Chemistry is then inherently a subject about abstractions, because it deals with the simplified, ideal cases of pure samples of substances that are only rarely met outside of the laboratory.

Teaching students about chemical substances can either involve starting with familiar materials and later considering how they are chemically constituted, or teaching through the more traditional chemical demonstrations involving reagents that are generally unfamiliar to learners. The latter approach is typically appreciated by younger secondary students (who often enjoy working in a real laboratory, with 'chemicals', and in particular Bunsen burners!), but may make it difficult to impress upon students the relevance of chemistry to everyday life and the ubiquity of chemistry in the environment. A key challenge for the teacher of chemistry is to attempt to help students see the wide relevance of chemistry as a subject (Eilks & Hofstein, 2015), whilst retaining some of the awe and wonder that many students experience when first allowed to do chemistry practical work in the school laboratory.

The chemistry triplet

One of the key ideas in chemistry education is what is sometimes known as the chemistry triplet, which is the idea that discourse about chemistry works at three levels. This idea was first popularised by Johnstone (1982) who suggested this principle applied, in somewhat different ways,

in biology, chemistry and physics. The idea has been seen as particularly useful and important in teaching chemistry, although it has been developed in a number of ways (Taber, 2013b; Talanquer, 2011).

The key idea is that learning chemistry involves -

- discussing phenomena at the level of what can be seen and handled;
- using explanatory models that invoke conjectured entities at a scale much too small to be visible (such as electrons, ions, and molecules);
- novel forms of representation that are part of the specialist language of the subject.

However, it is not simply that chemistry students need to be able to handle these three features of chemistry classroom discourse, but rather that teachers will often draw upon, and move between, them within a single segment of teacher talk.

There are several features of this challenge that each contribute to the difficulty of learning chemistry. To some extent these are problems inherent in teaching and learning chemistry and it is not suggested teachers can or should seek to avoid them. However being aware of how unfamiliar and complex the subject matter can seem from the learners' perspective allows the teacher to scaffold students' learning by (a) not introducing too many complications at once, and (b) being explicit about the levels being referred to and any shifts in level that are made.

Re-describing phenomena at two theoretical levels

The first aspect of learning chemistry that can be difficult for students is how chemists talk about chemical phenomena such as something burning - for example when igniting the natural gas supply to use a Bunsen burner. The phenomenon - what the student experiences - is the light and heat produced by the flame. The chemist describes this process at two levels (see figure 1). Firstly, it is conceptualised in terms of technical categories and concepts at the macroscopic (bench) scale - as a type of chemical reaction between two substances referred to as combustion and which is a subcategory of a wider class of reactions known as oxidation or redox reactions. This already poses quite a learning demand on the student not familiar with these ideas. Then it is common to re-describe what is seen at the macroscopic scale in terms of submicroscopic molecular level models - bonds breaking in reactant molecules and the formation of new molecules of the products. So here students are expected to think with, and develop accounts of chemical changes using, a whole realm of unfamiliar and abstract entities that have been invented by scientists. To say invented rather than discovered is not to suggest that molecules and the like do not really exist,

but rather that these submicroscopic models are inventions in the sense of ideas thought-up to make best sense of empirical data that provides evidence of the nature of matter at an extremely small scale (see the chapter 'Reflecting the nature of science in science education').

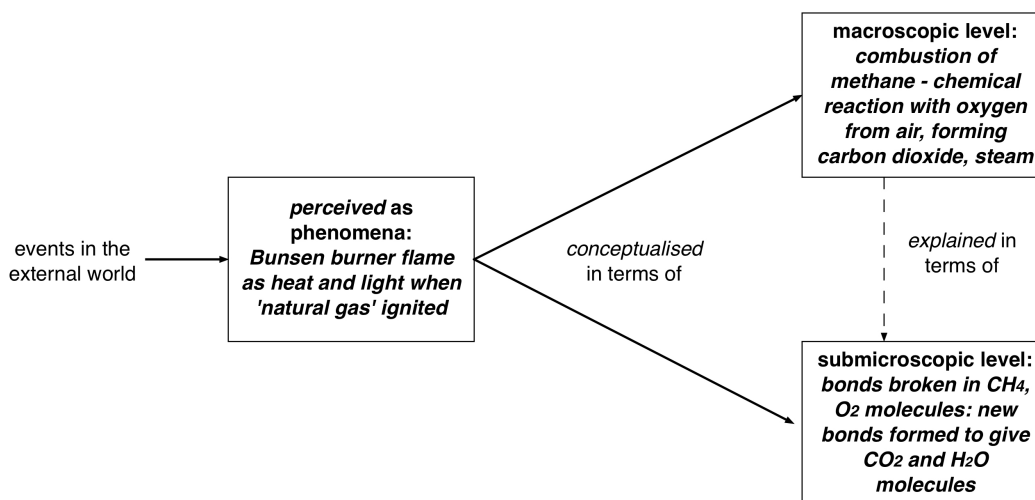


Figure 1: Chemists re-describe observable phenomena in theoretical terms at two levels (after Taber, 2013b, figure 2)

The challenge of adopting the chemists' particle models

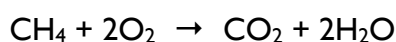
Scientists consider that the observable behaviour of the material world arises as emergent properties of vast numbers of molecules and ions interacting together. That is, the unfamiliar (and sometimes counter-intuitive) properties of particles so small that quantum effects become significant give rise to quite different properties of matter on the scale that can be directly observed. For example, atoms, ions and molecules do not have definite surfaces, but rather have indeterminate volumes (with their electron 'clouds' becoming less dense the further from the nuclear cores). Yet when enormous numbers of molecules or ions clump together to give visible particles of matter these have (at observable scales) definite surfaces, and volumes that can be precisely measured.

Learners however commonly misunderstand the logic of the particle model as emergent properties of a complex system, and instead assume that materials have the properties they do because they are made up of particles with those particular properties (so they may assume that butter is made of soft particles; glass is made of transparent particles; copper is made of conducting particles, and so on). This is just one area of chemistry where students form alternative

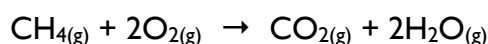
conceptions that are inconsistent with scientific thinking (see the Chapter '*The Nature of Student Conceptions in Science*').

Bridging the two theoretical levels using ambiguous representations

Another complication occurs at the symbolic level, where particular specialist forms of representation are adopted in chemistry (Gilbert & Treagust, 2009). One aspect, explored further below, is the range of different forms of representation used in the subject. A particular issue, however, is how some core forms of representation are ambiguous in terms of their reference to either the macroscopic or submicroscopic scale. So, for example,



or



is an example of a very common form of representation of chemical reactions (chemical change): the chemical 'equation'. Yet this same representation could be referring to the 'macroscopic' bench scale (where two moles of oxygen are required to fully react with each mole of methane), and where the equation implies 16g of methane react with 64g of oxygen to produce 44g of carbon dioxide and 36g of water (see below); or to the explanatory model at the ('submicroscopic') molecular level where the reaction is understood in terms that each molecule of methane interacts with two molecules of oxygen. (This is a conceptual model simplifying what is actually likely to happen in the chaos of a real flame with various molecular fragments moving around at high speeds.)

As the same equation can refer to either of these different conceptualisations, such representations can act as a kind of conceptual bridge (see Figure 2) that allows the teacher to shift the explanation between these two levels, and so connect the chemical description at the macroscopic, bench level with the explanation in terms of theoretical particle models. That is very useful, but clearly can potentially confuse learners unless the teacher is very careful to be explicit about when they are referring to each level, and when they are making shifts between levels.

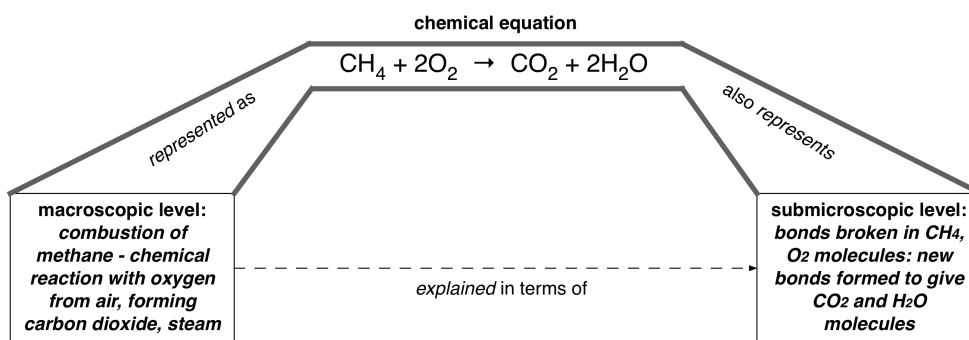


Figure 2: Using symbolic representation to bridge the two theoretical levels of chemistry

Oversimplification may act as an impediment to conceptual development

Another challenge for the chemistry teacher when introducing students to abstract and unfamiliar ideas is that students will often adopt what are intended as models, general rules, heuristics, approximations, and the like as definite and absolute (see the Chapter '*Models and modelling in science and science education*'). Students often see science as a subject providing factual descriptions of the world, whereas scientists are often offering theoretical accounts. Students may take models (both scientific models, and teaching models used to simplify complex material) to be precise representations of what is being modelled, and may consider analogies and metaphors used to help make the unfamiliar familiar to be intended as precise and literal accounts (Treagust, Chittleborough, & Mamiala, 2002).

A spiral curriculum (Bruner, 1960) enables teachers to revisit ideas at greater levels of sophistication to build up student knowledge over time. This is important, as unfamiliar material needs to be introduced in manageable learning quanta, and such new learning is often initially quite labile and tenuous unless it is subsequently regularly reinforced. Only once well consolidated is such learning robust enough to act as foundations for further learning. So complex ideas may need to be revisited in diverse contexts, and then developed over extended periods of time. However, the teacher needs to be aware that teaching sequence can have unintended effects. For example, it is common for students to develop alternative conceptions of ionic bonding and to assume ionic substances contain molecule-like groups of ions. It seems likely that learning about covalent bonding in simple molecules sets up a bias, or expectation, through which teaching about ionic structures is interpreted. (The common use of formulae representing the simplest ratio of ions, e.g. NaCl for sodium chloride, can also mislead students to assuming the basic unit is $\text{Na}^+\text{-Cl}^-$.)

When chemical reactions are first met and represented by equations the examples used tend to be of reactions that (in effect) 'go to completion', that is where the reactants are changed (virtually) completely to products (something represented by the \rightarrow symbol). Usually students have some years of working with such chemical equations before meeting the idea of chemical equilibria, by which time they may well find it difficult to modify their conception of a chemical reaction. Arguably then, the possibility of reactions that do not go to completion, illustrated with a few common examples, should be introduced when students first meet the formalism of chemical reactions so they will not form a fixed conception that is difficult to modify later (when the teacher prefers them to think of all reactions as potentially equilibria, and those that can be considered to go to completion under particular conditions as the special cases).

Some other examples of the potential for introductory teaching itself to act as 'pedagogic learning impediments' (Taber, 2014) to later teaching are:

- seeing the metal to non-metal dimension as a dichotomy (i.e. an element is clearly either a metal or non-metal, rather than falling somewhere on a scale of electronegativity);
- seeing covalent and ionic bonding as a dichotomy (so, for example, when polar bonds are met they are assumed to be a type of covalent bond);
- learning a model of atoms based on electron shells without appreciating its nature as a model (interfering with later learning about orbital models);
- learning about neutralisation based only on examples of strong acids reacting with strong alkalis (so developing an alternative conception that neutralisation always leads to neutral products);
- learning about pH using standard indicator paper (so assuming strong acids have pH 1, and that this is the minimum of the pH scale).

Teachers do need to simplify complex ideas and focus on uncomplicated examples when first teaching abstract material - but also need to acknowledge the existence of complications from the start so that learners do not adopt overly rigid notions that can be difficult to shift once established. Arguably teachers should (usually!) make it a habit to qualify general statements with 'generally', 'normally', 'usually', 'often', 'typically', and similar terms. If students are told, and learn that - for example - combustion is *usually* a reaction involving oxygen, they are better prepared to make sense of reactions such as the combustion of iron in chlorine. If however they develop a conception that combustion *always* involves oxygen, then they will find it difficult to later learn about combustion in chlorine without misinterpreting the teaching (for example, assuming that iron and chlorine are both reacting with oxygen). Research on how students remember science that does not fit their expectations suggests that even when students seem to accept what they are taught at the time, their later recollections can be distorted. So even if learners seem to accept

in the lesson that they have seen a combustion reaction that was a binary synthesis between the two elements iron and chlorine, they will likely later remember this as being a reaction involving oxygen if they already 'know' that combustion is burning in oxygen.

Metaphors, similes and analogies are important teaching tools to help make the unfamiliar familiar to learners, but need to be used as conceptual bridges that can only support progression in learning when they are quickly passed over and soon left behind. The common teaching analogy that the atom is like a tiny solar system may have some potential value (when learners are familiar with the structure of the solar system, but not of atoms), but can easily lead to students adopting negative aspects of the analogy as part of their model of the atom - assuming that gravitational forces act to keep electrons in the atom for example (Taber, 2013c).

Another example is the common use of social metaphors to talk about the behaviour of atoms and molecules. Teachers may use anthropomorphism to put molecular activity into a narrative that is more familiar to students: but students commonly adopt and retain this way of talking and thinking, and this contributes to the very common alternative conceptual framework (Taber, 2013a) that explains chemical processes in terms of what atoms want (i.e., the atom needs a full shell of electrons), rather than in terms of physical models such as bond strengths, energy levels, and electrical forces. In all these different cases sensible pedagogic choices can have unintended and unhelpful outcomes. General advice to the teacher of chemistry is:

- regularly emphasise the nature of scientific models and be explicit about the nature of typologies, models, general rules, etc met in chemistry as useful thinking tools but not absolute accounts of nature;
- be explicit about the use of teaching models, analogies, metaphors and the like: make sure students are aware of their limitations as well as their value, and only use them to bridge to the concepts being introduced (e.g., if later students use them as if scientific accounts, reflect back their comments by rewording their points, modelling the scientific language);
- focus on simple examples when introducing abstract ideas, but be clear when the examples used are special cases that do not fully reflect the concept being taught (as with neutralisation to give neutral products, or chemical reactions that go to completion, or combustion in oxygen).

Using chemical formulae as thinking tools

There are actually a great many kinds of representations used in chemistry, beyond the ubiquitous use of formulae (CH_4 , O_2 , NaCl , etc.) and equations. However, even these core representations may be extended in various ways such as when undertaking chemical calculations (see figure 3), or

when exploring changes in oxidation state to demonstrate that a redox reaction has a balance of oxidation and reduction steps (see figure 4).

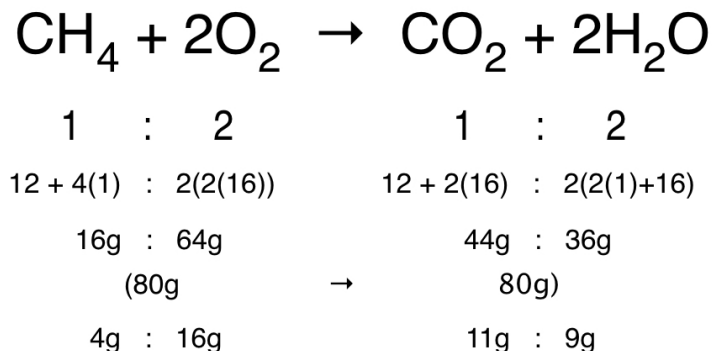


Figure 3: Representing mass relations in the combustion of methane

Figure 3 shows annotation of the basic chemical equation with a series of lines of numbers. Immediately beneath the balanced equation is a representation of the number of molecules of each reactant and product species (one molecule of methane reacts with two molecules of oxygen to form one molecule of carbon dioxide and two molecules of water). As the equation can bridge between the particle model and the macroscopic description, this also represents the mole ratios in the reaction: one mole of methane reacts with two moles of oxygen. Therefore it is possible to work out the ratio of reacting masses using the relative atomic masses to calculate molecular masses, and so molar masses - again making use of the ability to scale between molecules (one molecule of methane has a mass of 16 relative atomic mass units, so one mole of methane has a mass of 16g). As the equation is balanced (the same number of atoms of each element - carbon, hydrogen, oxygen - appear in the products as in the reactants), mass must be conserved - which it is: 80 grammes of reactants gives 80 grammes of products. Finally, a ratio is conserved by scaling each component, so we can find the simplest representation for the ratio using integer values of mass (4:16::11:9).

Figure 3 is readily understood by the chemist or experienced chemistry teacher. This kind of representation is useful because it allows us to represent a good deal of chemical thinking, and relates our theoretical model of what is going on in terms of molecules with actual laboratory operations. Some pupils however may tend to panic as soon as the teacher writes a chemical equation, and others may despair at the first sight of mathematics being applied in the subject - so these powerful formalisms need to be carefully introduced. The representations support shifts in thinking between the molecular and the macroscopic - but something that is a bridge between

levels for the expert can become a barrier to comprehension for the novice. Powerful representations such as these are important in teaching, but need to be introduced in stages, and with a good deal of verbal scaffolding, if students are to understand the formalisms and appreciate the power of the representational tool. Most students will need opportunities to work through examples and become confident working at each stage (e.g. identifying mole ratios, before considering masses) so as not to overload working memory with too much new information at once.

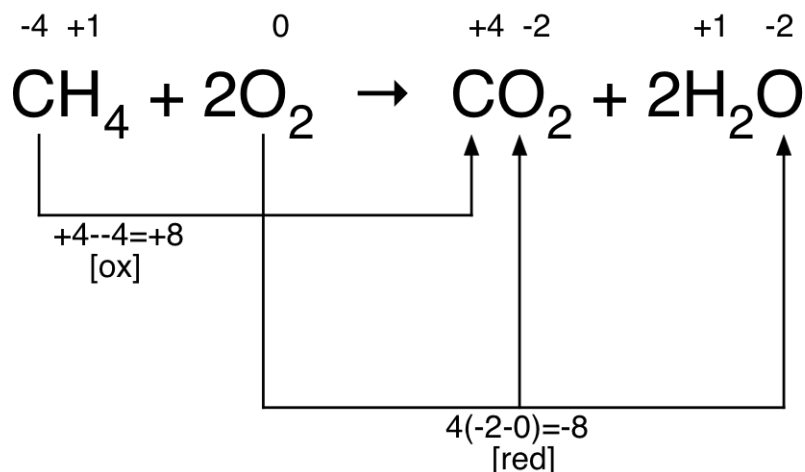


Figure 4: Representing a redox process

Figure 4 considers the same equation, but annotated in a different way. This time oxidation states for each element in each substance are designated, and this is used to identify changes in oxidation state (i.e., final oxidation number minus initial oxidation number) and so where oxidation occurs (the oxidation states of carbon increases) and where reduction occurs (the oxidation state of oxygen decreases). The formalism used here also demonstrates that (as must be the case in a balanced equation) the total number of oxidation steps is balanced by the total number of reduction steps - eight in each case.

This links to the need to conserve charge in chemical changes - although in this reaction the reactants and products are all comprised of neutral species. This form of representation then not only draws upon mathematics (albeit very basic arithmetic) but also relates to an additional abstraction from what students can observe - beyond both seeing the flame of burning laboratory gas as a reaction between chemical substances, and then seeing those substances (invisible gases) as composed of a multitude of submicroscopic molecules. Oxidation states here reflect treating covalent substances, as if they were ionic. Oxygen is more electronegative than carbon so in the

carbon dioxide molecule the charge distribution is more akin to $C^{4+}O^{2-}_2$ than to $C^4O^{2+}_2$ (although actually it reflects neither of these extremes). The logic of oxidation numbers is to consider how a molecule might most readily ionise (i.e. a hypothetical, mental operation). Most chemical compounds are somewhat between the ideal models of covalent and ionic bonding, and so can be considered as a resonance of different canonical forms (see figure 5). The ionic form would not exist under normal chemical conditions as the highly charged carbon cation would be too unstable - although students may not realise this as one of the most common alternative conceptions in chemistry is that any species with an octet of valence electrons or a full outer shell is stable (Taber, 1998).

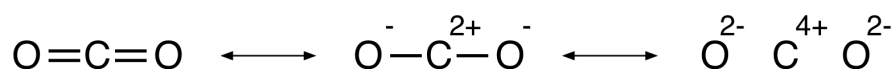


Figure 5: Representing the carbon dioxide molecule as ions

Figure 5 then represents a particular conventional formalism used in chemistry to represent a theoretical mental operation carried out on conjectured submicroscopic entities (molecules) as part of an abstract explanatory scheme. The links between such a representation and the phenomena students can actually observe in chemistry are - to say the least - indirect.

Element is a manifold concept

Students here also have to cope with how chemists use one of the most fundamental concepts in the subject - element - in multiple ways. An element is a pure substance that cannot be broken down into anything more simple or basic by chemical means, and is considered to be comprised from only one type of atom. This basic concept is inherently challenging when first met. For one thing it is not obvious from observation what makes one substance more fundamental than another. For example, heating different substances in air might lead to decomposition (to something chemically more simple), or to combustion (which if what is heated is an element leads to something chemically more complex), or to melting, and evaporation or boiling; or sublimation (changes of state without any chemical change and so no change in chemical complexity). Without already knowing whether the substance being heated is an element or not, there is no obvious sign of whether the process produces something chemically more simple. Solids are inherently more ordered than liquids, or gases, which have component particles with more 'degrees of freedom'. So the physical changes produced by heating do reflect changes in levels of complexity - but not in a

chemical sense. This distinction is not something that a student can infer from simply observing a substance being heated.

Describing the substance in particle terms is more straightforward - methane contains two types of atom, and oxygen only one. So oxygen is an element. However, oxygen does not comprise of atoms, but molecules where the constituent parts of two atoms have been reconfigured into a molecule (which is not understood in chemistry as just two atoms 'stuck' together, but rather the result of an interaction which leads to chemical bonding, conceptualised in terms of energy states, or the formation of molecular orbitals - ideas not readily understood by novices recently introduced to the idea of atoms). Moreover, the 'same' kind of atom, for this purpose, potentially incorporates different isotopes - as chemically the proton number is critical, but the neutron number is generally of little, chemical, consequence. Again this seems familiar and obvious to the chemist or science teacher, but is another complication to be made sense of by students when first meeting these ideas.

Yet there is an even more challenging aspect to the chemist's thinking here. A common alternative conception that many students develop is the common-sense assumption that a compound should have a combination of the properties of its constituent elements. The chemistry teacher has to emphasise that compounds are not mixtures of elements but unitary substances in their own right, and that when new substances form in chemical reactions they have their own individual properties. No sane person would want to add a mixture of a very reactive inflammable metal and a choking gas to their meals, yet sodium chloride - table salt - has traditionally been used for just that purpose. The compound has very different properties than the elements sodium and chlorine, and whilst too much salt added to food can increase blood pressure, NaCl is not generally seen as a serious chemical hazard. Indeed, a fair proportion of the species on the planet live out their lives immersed in sea water, an impure solution of salt. So a key teaching point in the subject is that the *elements are not present in their compounds*, as a sample of element ceases to exist when it reacts to become a new substance.

Yet figure 4 represents how, despite this core principle, chemists feel justified in assigning oxidation states to the 'elements in' compounds even though no elements are actually present. The element concept then has several related but distinct meanings, and *there is a sense* of an element as a kind of essence that survives into compounds and can be isolated again. The element is 'in there' because it can be retrieved. The particle model suggests that what is actually unchanged is atomic cores - as chemical change does not influence the nuclei, or usually inner electron shells, present.

We can recover the element through various chemical (or electrochemical) processes as at a particle level what determines the element is the nucleus (with its particular proton or atomic number) which is unperturbed by the chemical changes going on around it reconfiguring the arrangement of atomic cores and valence electrons. So the numbers written above the element symbols in the compounds in the chemical equation in figure 4 - the oxidation states - refer to the oxidation state of the element _[essence] in its combined form where we are using the term element in a distinct way (i.e. not the element_[substance] that we usually mean in chemistry). If the teacher is not aware of, and careful about, how they talk about 'elements' in these different ways there is clearly considerable scope for confusing and frustrating learners.

Other forms of representation used in chemistry classes

Other forms of representation commonly used in chemistry include graphs, such as those recording changes of temperature, pressure or volume during a reaction. Graph-like schematics such as reaction profiles (e.g. figure 6) are also commonly used. Here what is plotted on the y-axis is the abstract notion of energy (variously calculated as free energy, enthalpy changes, bond energies etc.), whilst the x-axis reflects the change in configuration of the molecular components as first bond fission, then bond formation, occurs. Although schematic in nature these types of representations can be developed in relation to aspects of reaction kinetics, the effects of catalysts, and reaction mechanisms (which are mental simulations of the conjectured processes of molecular interaction, deconstruction and reconfiguration during the reaction) i.e. showing transition states (the most unstable conjectured configurations during the process) and the formation of intermediates that can under some circumstances be isolated. Again then, learners are presented with formalised representations based on imagined operations on the conjectured submicroscopic entities used to develop theoretical explanations of what can actually be observed in the laboratory.

Various ways of representing the particles at the molecular scale are also widely used in chemistry (Taber, 2009). Atoms may be shown as circles, or concentric spheres, or with scatter-type figures showing electron density, or with lobes representing orbitals and so forth. Bonds may be shown by lines or dots (electron pairs) or contour lines or density of grey or dot scatter. Atoms (or strictly atomic cores) in molecules may be shown by their elemental symbols, or their nuclear charge. Complex organic molecular structures are often shown in a skeleton form with C-C bonds as default and hydrogen atoms bonded to carbon centres excluded (such as in the second image in figure 7). The chemist or science teacher becomes so used to this range of representations that

they learn to 'see' past the specific formalism to what is represented. However, for the novice, these variations may be salient and seem very significant (Taber, 1994).

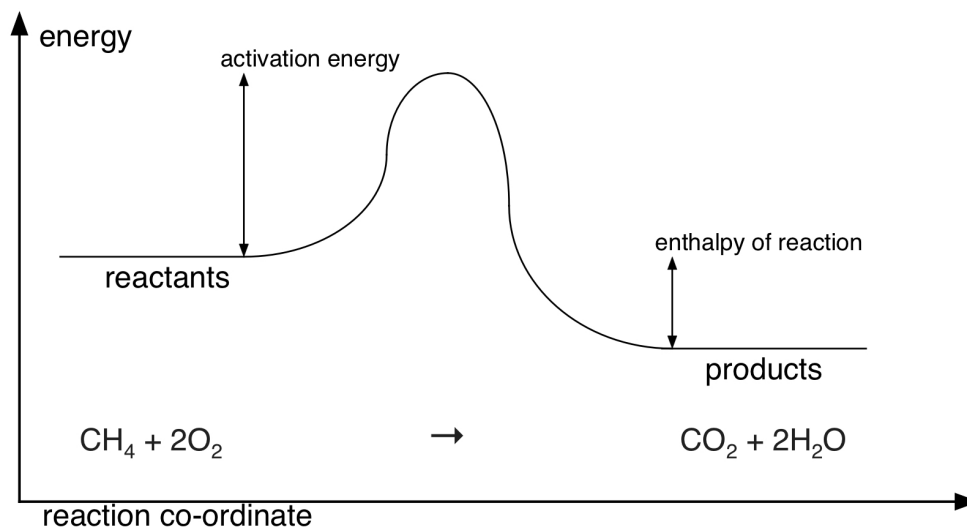


Figure 6: Representing the 'reaction profile' as a reaction proceeds

Some molecular representations involve further abstraction or complications - such as circles inside hexagons for aromatic groups (see figure 7), and the use of element-like symbols for radical groups (Me for $\bullet\text{CH}_3$, Et for $\bullet\text{C}_2\text{H}_5$, Ph for $\bullet\text{C}_6\text{H}_5$, etc.), or symbolism to show three dimensional structure (for example in stereoisomers). As one example, figure 7 presents three different ways of representing a molecule of one substance: phenol. Unless learners are carefully supported in learning such formalisms they will construct their own meanings for the symbolism involved - for example, students have assumed that the circle in a hexagon representing the aromaticity of a benzene ring is meant to show a container for 'spare' electrons in the structure.

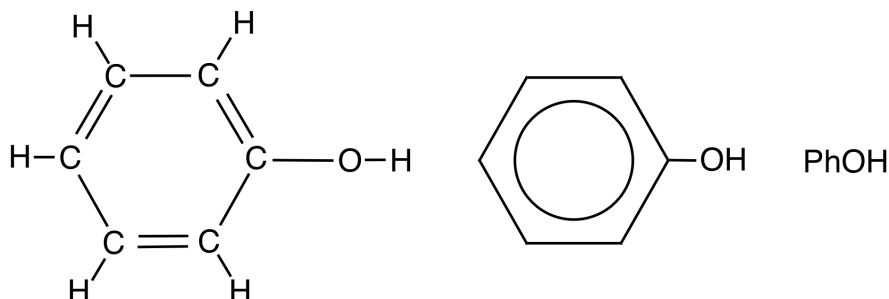


Figure 7: Three representations of the phenol molecule structure

These are all forms of representation that can appear on the page or screen, but chemistry also uses various kinds of structural models to represent molecules and lattices. Again there are different formalisms used (such as touching spheres in some crystal models, or representing bonds between atomic centres with springs or straws or sticks). All of these different forms of representation have been developed to help communicate specific aspects of the subject matter of chemistry - yet each new form of symbolism or representation adds to the material to be learnt and mastered by the student. This does not just mean recognising a suitable interpretation, but being able to select the most appropriate form of representation from among a number of possible options when communicating ideas. Students therefore need to not only be introduced to the forms of representation themselves, but also to their particular affordances and ranges of application. Again this is an area where the teacher, often being very familiar with a wide range of representational tools for discussing chemistry, needs to be careful to scaffold student learning. As in most areas of learning, students need to meet ideas in manageable learning quanta, and then to have opportunities to apply the ideas in a range of contexts, with regular review to consolidate learning.

This could seem very negative, but is not all bad news for the teacher. For one thing, it is believed that learning is often more effective when it is multi-modal - so for example when verbal descriptions are accompanied by diagrams and models (Jewitt, Kress, Ogborn, & Tsatsarelis, 2001). Chemistry naturally lends itself to this kind of multi-modal teaching. Effective teaching needs to link together the phenomena seen in the laboratory with the descriptions at both macroscopic and submicroscopic scales and various relevant forms of representation - and this draws upon verbal description, gesture, diagrams, models, simulations etc.

Opportunities to challenge the most able (gifted) student

This chapter has deliberately focused on some of the fundamental challenges of teaching and learning chemistry, but concludes by suggesting that these very complications make chemistry an excellent subject to challenge the most able learners and to teach about the nature of science. Effective classroom teaching is educative because (a) students are faced with challenges that force them to shift out of their 'comfort zones' (where they can work algorithmically to undertake tasks that are in effect exercises), and rather experience genuine problems that require them to develop their thinking, but (b) tasks are scaffolded by teachers so that problems are soluble with the amount of support provided to particular students. Good teaching then offers the right balance between challenge and support. For many learners first meeting the ideas behind chemistry, the

emphasis needs to be on scaffolding support so that students are eased into new ways of thinking. For the most able students, however, who (at least in some national contexts) seldom find school science lessons genuinely stretch them, there are opportunities for the teacher to present significant levels of challenge to these students (Taber, 2010).

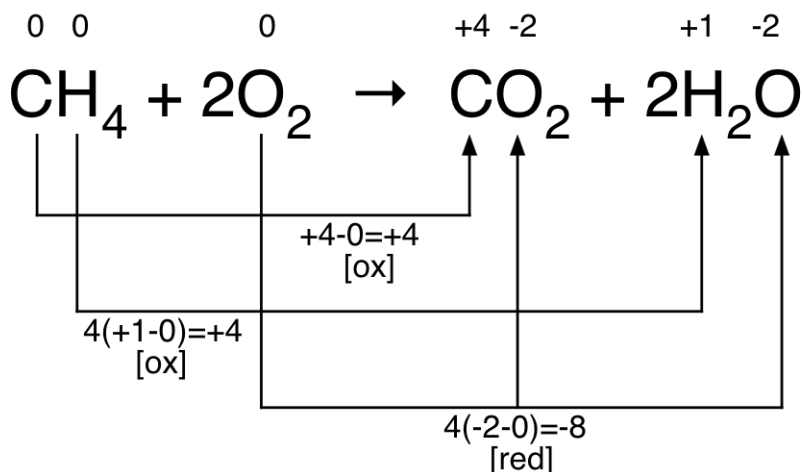


Figure 8: Representing an alternative conceptualisation of a redox process

As one hypothetical example, where most learners might initially struggle to understand the ideas behind figure 4, a gifted learner in a class might point out that carbon is only somewhat more electronegative than hydrogen, so it would be possible to offer an alternative version of figure 4 (see figure 8) where the carbon is considered to be oxidised by fewer steps, and where the oxidation state of hydrogen increases as well. This could be supported by arguing that although the methane molecule is, theoretically, somewhat less likely to form $\text{C}^{4+}\text{H}_4^-$ rather than $\text{C}^4\text{-H}^+$ (i.e. by drawing the resonances, cf. figure 5) the similarity in electronegativity between carbon and hydrogen makes any ionic form of limited relevance to the structure. A teacher should be impressed by a student offering such a suggestion as it would show they understood and were actively engaging with the ideas met in class. The gifted student may also point out that alternative notions of oxidation (oxygen is added to hydrogen as well as carbon) as well as the relative degrees of polarity in the bonds in CH_4 and H_2O suggests that figure 8, with hydrogen also being oxidised, is a preferred analysis. This kind of discussion (about abstract theoretical models and formalisms) is likely to be highly motivating for a gifted student who has quickly acquired robust understanding, but in most classes is best carried out privately as it is likely to only confuse and mystify many classmates with a more fragile grasp of the basic ideas that require further consolidation before they can be used as the foundations for further learning.

Opportunities to teach about the nature of science in chemistry

Part of the reason students often find school science becomes dull once past the initial excitement of being allowed to work in laboratories is that it can seem an endless list of things to be learnt - things previously discovered and so already known. The various models, and formalisms, used in chemistry could easily fall into this category. There is also an inherent issue of relevance to students' lives in chemistry. Chemistry is a widely applicable and relevant science, but usually the applications are at least one step removed from the ideas met in school science (again because chemistry works with substances and so is a level of abstraction away from the materials science of more direct relevance).

Something to aspire to here then is what has been termed epistemic relevance (Taber, 2015). This means that rather than teaching students a wide range of chemical ideas and models - especially when research suggests students often have limited appreciation of the nature and roles of models in science - and then try to show how these have applications, it is better to present students with chemical phenomena that can generally fire their imagination and use this as a starting point for showing students how science involves an interplay between empirical evidence and theory, and so how theory taught in chemistry is motivated by the desire to explain actual observations.

It is not suggested that students will easily arrive at the concepts, category systems, models, and formalisms used by professional chemists (Driver, 1983). These will inevitably need to be introduced: but only once students have been set the task of making sense of phenomena and given an authentic experience of what it is to try to develop new ideas and representations to explain, report, and predict chemical phenomena. By contrast much current practice involves teaching students about other people's solutions to *problems they have never had*. A more authentic chemistry education may need to limit its scope in terms of the topics covered, but will give a much better flavour of chemistry as science rather than just a catalogue of facts and strange categories and formalisms.

Some readers may wonder if it is counterproductive to ask students to develop their own representations given that these will inevitably need to be put aside in favour of taught conventions. Yet such activity can support effective learning (Tytler, Prain, Hubber, & Waldrup, 2013). If groups work on developing their own representations and formalisms, and have to argue for the logic of their approach, they will come to appreciate both (i) that many of the representations used in chemistry are historically contingent and not in some way inevitable (as different groups will devise different alternatives), and (ii) how science comes to adopt such conventions through

argumentation and community agreement. They will also better appreciate that the processes of science are creative and call upon imagination - and are often only widely accepted after being refined by extensive work (see the Chapter '*Reflecting the nature of science in science education*').

There are widespread calls to involve students in more genuine enquiry in science lessons (Osborne, 2014). Enquiry processes encompass all stages of scientific work (see the Chapter '*Learning Science through Inquiry: Opportunities and Challenges*'). There are limits to the kinds of student-initiated chemical investigations that can be safely carried out in school laboratory conditions (in those countries where these are available) but the teacher can use standard chemical demonstrations and class practicals as starting points for exploring the other side of enquiry - the scientific work of finding ways to construct understanding of the world.

Further reading:

Chemistry Education Research and Practice: The top ranking research journal on chemistry education is provided free to access for all readers by the publisher (The Royal Society of Chemistry) - at pubs.rsc.org/en/journals/journalissues/rp#

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