Chapter 4
Learning at the Symbolic Level

Keith S. Taber

Abstract The symbolic language of chemistry is extensive, and is used ubiquitously in teaching and learning the subject at secondary level and beyond. This chapter considers how this 'language', which acts as such a powerful facilitator of communication for the expert, may often impede effective communication for novice learners. Symbolic representations become second nature to the teacher, being highly integrated with conceptual understanding and subject knowledge. However, such representations may make considerable additional demands on learners already challenged by both the abstract nature of concepts and the range of unfamiliar substances to which these concepts are applied in the curriculum. Drawing upon a broadly constructivist perspective on learning, the chapter explores three aspects of learning about the representational level in chemistry. The range of representations that are used in teaching and learning chemistry at school and college levels is outlined, drawing attention to the demands this makes of those setting out on a study of chemistry. The particular example of the 'chemical equation' is then considered in some depth to illustrate the extent to which representational features are linked to underlying chemical theory, and how students are expected to appreciate the nuanced distinctions between different variations in representation (whilst ignoring trivial stylistic variations). Finally the role of the symbolic level of representation as a mediator between the molar and sub-microscopic levels of chemistry is considered, and how this offers potential to compound student learning difficulties, but also opportunities for reinforcing student understanding. Throughout the chapter there is an emphasis on where teachers need to give careful thought to support student learning and facilitate progression in the subject.

The Symbolic Language of Chemistry and Chemical Education

This chapter considers the nature of the symbolic level of representation in chemical education. It begins by suggesting why the use of symbolic representation in com-

K.S. Taber (✉)
University of Cambridge, Cambridge MA, UK
e-mail: kst24@cam.ac.uk

municating chemistry to learners can be a source of learning difficulties. The range of abstract representations used in chemistry teaching as students progress through basic chemistry to more advanced studies is then briefly reviewed. This is followed by a consideration of one particular class of representation that is ubiquitous in chemistry and chemistry classes – the chemical equation. This will show both that (a) understanding chemical equations depends upon relating the symbolism to underpinning assumptions and domain knowledge, and (b) that even within this one class of representations there is considerable variety of form, such that students are expected to progress through increasingly complex types of equation that reflect subtle variations in format and meaning.

The chapter then turns to a consideration of how the symbolic level relates to other levels of representation in chemistry. As discussed earlier in the book (see the Introduction to this volume), chemistry is presented in classrooms and lecture rooms in terms of references to the molar properties and behaviour of substances, i.e. in terms of observable and measurable phenomena; in terms of explanatory models of various types of hypothetical particles (often discussed as if as real as the substances themselves); and in a wide range of symbolic representational forms. It has been well recognised that teaching often involves shifts between the molar or macroscopic level, and the conjectured sub-microscopic world used to make sense of the observed phenomena (Jensen, 1998). These shifts have been identified as potentially problematic for learners (e.g. Johnstone, 2000). This is both because of the abstract nature of the particle models, which may themselves present challenges to most learners (e.g. Harrison & Treagust, 2002), and because of the gap in background knowledge and experience between teachers and their students – such that teachers have developed the fluency to effortlessly shift between 'representational levels', where students lacking such strong familiarity with the material may struggle to even recognise when such shifts have taken place.

It will be suggested that the role of the symbolic level in mediating discussion of the macroscopic and sub-microscopic levels not only offers another layer of complexity for learners, but through *its ambiguity* (where symbols may often represent either macroscopic or sub-microscopic levels) offers scope for the novice learner to confuse discussion of the macroscopic and sub-microscopic levels.

An Invitation to Revisit Chemical Representations at the Learners' Resolution

The key message is that aspects of symbolic representation that are familiar and taken for granted by 'experts' (i.e. chemists, science teachers etc.) may not always be well understood by students. This has been found even at university level (Marais & Jordaan, 2000). A primary aim of this chapter is to *make explicit* some of this complexity and abstraction, to remind 'experts' how apparently straightforward aspects of our symbolic representations can actually present a significant demand on learners who lack:

- a strong familiarity with the symbolism;
- a sound theoretical grasp of the conceptual principles that are assumed/implied when using the symbolic representations; and
- a wide repertoire of familiar chemistry to draw upon as exemplars and referents for the symbolic representations.

A teacher able to consider how chemical symbolism is perceived 'at the learner's resolution' (Taber, 2002a) will be better placed to appreciate how abstract, arbitrary and confusing much of this symbolism must seem to those just embarking on a formal study of our subject.

An Educational Thought Experiment on Working Memory and Chemical Symbolism

One key concern here is the limitation of 'working memory' which restricts the number of chunks of information that can be manipulated when solving problems or carrying out other cognitive tasks (Miller, 1968). It has been shown that the cognitive demand of a task increases with the amount of information that needs to be coordinated to achieve the task (Tsaparlis, 1994). Although working memory does not seem to develop more 'slots' as learners mature, familiarity with conceptual material allows it to be 'chunked' (so each 'slot' holds more information). A chunk in this context is 'an integrated piece of information, where remembering part of it will help you remember the next' (Baddeley, 1990: 42) that allows complex material to be accessed and processed as a single unit. As an example, consider Fig. 4.1:

Figure 4.1 is a symbolic representation of a chemical entity. Consider a simple educational thought experiment whereby a group of chemists and non-chemists (of similar intellectual ability) are shown the figure, and then some time later asked to sketch what they recall. The non-chemists are likely to remember varying amounts of detail of the image, but few are likely to be able to reproduce it sufficiently so that it has *the same chemical meaning*. To the non-chemist, this is a complex figure that, despite its symmetry, is likely to be seen as comprising many components – too many chunks for most people to readily memorise.

We would expect most of the chemists to be able to produce a figure that much more closely reflects the original. Indeed for a chemist simply recognising (*recognising*) the image as representing a dimer of ethanoic acid should enable a chemically equivalent figure to be readily produced later. The conventions of representing atomic centres and different types of bonds in this form of structural formula should allow a fairly faithful representation of the actual components of the image. In effect, two chunks of information (what is represented, which type of representation)
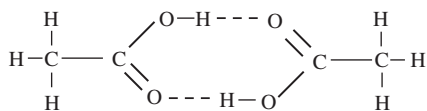

Fig. 4.1 A complex pattern or a simple representation?

suffice to code the image, as *by drawing on appropriate background knowledge* the detail can be reconstructed as the components follow a familiar order. The non-specialists see a collection of letters and lines that may seem to be in an arbitrary configuration, rather than a recognisable gestalt that acts as a unitary symbol.

So it is helpful for the chemistry educator (teacher, teacher-educator, curriculum developer etc.) to be able to appreciate chemical symbolic representations at the novice learner's 'resolution', i.e. as they might appear without the highly evolved interpretative frameworks that only develop with increasing familiarity and experience of the knowledge domain. This helps us to appreciate what learners find challenging: and therefore when teaching needs to be informed by allowing for the cognitive demand of asking students to work with our specialist system of symbolic representation.

The Lingua-Chemica?

The various symbolic representations used in chemistry can be considered as being part of *a specialist language*,

> Chemists communicate in a highly elaborated alfabetic [sic] and symbolic language. The chemical nomenclature is a predominant literary language. Only short names are spoken, the official, sometimes very long terms are replaced by trivial names or are uncanonically abbreviated for oral communication. The chemical nomenclature works with a distinct syntax and semantic, but is not suited for textual sentences. Structures are drawn according to specific rules.
>
> Sliwka, 2003

The reader is invited to see chemistry students as similar to learners working in a second language, where they are expected to be both learning the language and using the language to understand substantive material simultaneously. This is considered more than a metaphor – and highlights the even greater challenge posed to those who are expected to learn this new language of chemistry *as* they learn the chemistry in the medium of a language that is already not their own. Internationally this will include a large group of students. It is not unusual for more prestigious universities to teach all subjects in English when it is not the native language (e.g. in Turkey). In some countries where there are many local languages, lessons in senior grades may be conducted in English (e.g. Ghana), and elsewhere policies to use English as the medium of science instruction in schools may be implemented to encourage eventual participation in scientific careers (e.g. Malaysia). For learners studying in these contexts the demands discussed in this chapter will be further complicated by the need to translate the English *as well as* the chemical language.

The Range of Symbolic Representations Used in Chemistry

Symbols are used extensively in teaching and learning chemistry and these symbolic representations take a wide variety of forms. The very common representation of chemical reactions through 'equations' will be used as the basis for much of the

discussion in this chapter, but it is also important to consider the range of different forms of symbolic representation that learners of chemistry are likely to face.

Letters, and sometimes numbers, are used *inter alia*:

- to symbolise element names (He, He, etc.) including some which are not obvious in English (Pb, Sn, etc.);
- for atomic number and mass (A and Z from the German words *Atomgewichte* and *Zahl*, Jensen, 2005);
- to stand for various measurable quantities for: amount of substance, mass, volume, pressure, wavelength, temperature, enthalpy, entropy (n, m, V, P, λ, T, H, S) etc.;
- and the units for such measurement (mol, kg, m^3, Pa, cm^{-1}, K, etc.), including compound units (mol dm^{-3}, J mol^{-1}, etc.);
- for various constants (k, h, $\hbar$, K_a, z etc);
- and mathematical relations such as changes, powers, inequalities (Δ, p {as in pH}, >) etc.;
- for structural features of crystals, f.c.c., b.c.c., c.c.p., h.c.p., 6:6 etc;
- to indicate oxidation states in systematic compound names, e.g. iron (II) chloride and iron (III) chloride; sodium trioxosulphate (IV) and sodium tetraoxosulphate (VI).

Alphanumeric symbols are also used in representing specific aspects of atomic and molecular structure (see below).

For learning to be meaningful, the learner has to associate new information with existing knowledge (Ausubel, 2000). This is the basis of the constructivist perspective on learning (Taber, 2000a, 2006) which reminds us that a learner's existing knowledge and understanding provides the interpretive framework used to 'make sense' of a teachers' presentation. In the normal course of events, however, neither the learner, nor the teacher, are explicitly aware of how the learner's specific 'constructivist goggles' (Pope & Watts, 1988) may be distorting the teacher's intended meaning. Ways of talking about and presenting chemistry that may seem perfectly sensible and clear from the expert's vantage point may actually be sources of confusion and misunderstanding at the learner's resolution. Sometimes the conventional symbolic representations we use in chemistry may act as such 'pedagogic' learning impediments (Taber, 2001a).

Symbols Used to Model Molecules

One key point to note is that many of the representations used in chemistry teaching are a combination of symbols *and* models: that is they involve both purely symbolic features and other forms of representation that involve less arbitrary features. For example, a figure such as Fig. 4.2 is a representation of one molecule (i.e. at the sub-microscopic level) of an allotrope of phosphorus.

Even a simple representation such as this assumes a good deal of background knowledge in those expected to 'make sense' of it. The representation combines graphical features meant to *model* the shape of the molecule, but includes symbols

Fig. 4.2 A representation of a
P_4 molecule
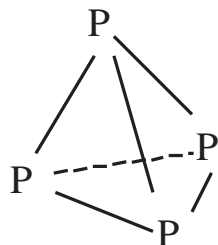
that have *conventional* meanings in this kind of representation. The lines represent the chemical bonds and the upper case 'P's (P being the symbol for the element phosphorus) the relative positions of the phosphorus atomic centres. To the reader who has a strong chemical background such a representation may be extremely clear.

However, it is worth considering the range of prior knowledge likely to be used in making such an interpretation. An expert is likely to be aware that phosphorus tends to have a valency of 3 or 5, (here each atom is bonded to three others); that the phosphorus centres will be arranged in a tetrahedral configuration; that bonds between elements with similar electronegativity are covalent, which is modelled in simple terms as a 'shared' pair of electrons, so that the bond involves the mutual attraction between valency shell electrons and atomic cores; that despite the impression that this entity is something like a pyramid (a regular geometric shape), the presence of non-bonding electrons means that the molecule is for some purposes better represented as a fuzzy shape of four overlapping spheres (see Bucat & Mocerino, this volume, for further discussion of representations of the sub-microscopic level).

At more advanced levels, a further set of symbols such as: C_2, T_d, O_h etc are used to described the symmetry properties of molecules, drawing upon ideas from group theory (Davidson, 1971).

Symbols Used in Modelling Electronic Structure

In chemical education we usually initially present molecules as if they can be understood as atoms joined together – an obvious simplification, if one that readily supports common alternative conceptions (Taber, 2003a) – before proceeding to the electronic level (Jensen, 1998).

A range of symbolic conventions is used in representing atomic and molecular structures at the electronic level. So for example double and triple lines are used for multiple bonds. This seems a clear convention, which helps keep check of valency rules. However the symbol '$=$' for a double bond is *not* intended to imply two equal bonds (which the symmetry of the symbol could seem to suggest) as σ and π components have different geometries, contributions to bond 'strength', and consequences for chemical properties. The novice learner may well find interpreting such representations a considerable challenge.

> Human perception is . . . inferred from fragmentary and often hardly relevant data signalled by the eyes, so requiring inferences from knowledge of the world to make sense of the sensory signal.
>
> Gregory, 1997, p. 1121.

Where the expert has developed interpretive frameworks that can 'see through' the symbols, the novice may focus on incidental aspects of the formalism used. There is a parallel with learning a written language system here. The novice focuses of the letter symbols that make up the words, where the fluent reader is barely conscious of these symbols much of the time, for example paying little heed to typeface or font used (McCandliss, Cohen, & Dehaene, 2003), and only focusing on the individual words when meeting something unfamiliar or apparently incongruous in what is being read.

Similarly, when A level (College level) chemistry students were asked to sort cards showing common representations of 'quanticles',

> "a generic term [used] to stand for molecules, ions, atoms etc., to distinguish them from macroscopic particles (e.g. grains of sand), and to emphasise the distinct 'quantum behaviour' of particles at this scale"
>
> (Taber, 2002b: 160),

some students saw past the specific forms of representation used (e.g. whether electrons were shown as dots, circles or crosses) to compare chemical features of the species represented. However, other students noticed and reported surface level *differences between representations* rather than accessing and applying knowledge about *the chemical species represented* (Taber, 1994).

When simple representations are used to introduce chemical bonding it is quite common for the electrons *in a single molecule* to be symbolised using both dots *and* crosses that are meant to indicate which atom electrons have derived from. This is in some ways a rather meaningless feature to represent as there is clearly no distinction between electrons (i.e. no equivalent of radioactive tracers), and no way of knowing where they are from (in the chaos of many reactions there is no certainty that a bonding electron in a product molecule was earlier when in the reactants associated with either of the atomic cores it now bridges). The expert chemist is well aware of this, and how *in this context* the distinction between the symbols is meant to be no more than an aid to electronic accountancy, to check the total number of electrons conserved in chemical changes. However, again, students may read more into the symbolism: for example suggesting that bond fission must be homolytic because each atom will 'get its own electrons back' (Taber, 1998).

The expert is aware that the electron's history has no significance, but a learner may well expect there to be a greater attraction between an atomic core and the bonding electron that 'belongs' to that atom (Taber, 1998). Such beliefs may seem rather bizarre for those used to thinking of chemistry in terms of fundamental concepts (such as energy and forces), but actually reflect one of the basic principles of magic that seem to commonly influence people's intuitions about the natural world (Nemeroff & Rozin, 2000). Indeed the notion that a past association leaves some

form of permanent linkage is not only a part of some influential eastern philosophies, but also reflects some aspects of modern physics at the most fundamental level (Capra, 1983).

Symbols are used to represent aspects of electronic structure in atoms, and the symbolism is augmented as a student progresses through different levels of study: e.g. those used to represent electron shells (K, L, M...); for orbital types (to s, p, d, f, sp^3, etc. in atoms; σ, π, δ, etc. in molecules); for description of electronic states ($^3P_1$, $^1S_0$, $^3A_{2g}$, $^3T_{1g}$, $e_g^1 t_{2g}^1$, $^3T_{2g}$). Introducing the added complexity of the time dimension, electronic transitions can be represented as shifts between shells, orbitals or states.

At secondary school level, students are introduced to the formalism of representing atomic structure as 2.8.1 (sodium); 2.8.7 (chlorine); 2.8.8.2 (calcium) etc. This symbolism has a simple relationship with the kinds of diagrams commonly used to represent simple planetary orbit-type models of the atom at secondary school level, and as long as the rule that counting starts on the innermost circle (i.e. electron shell) is followed this is relatively straightforward. However at college (sixth form/senior high school) level, more complicated atomic models are introduced which are more abstract, more difficult to represent in simple diagrams, and lead to more complex symbolic representations: $1s^2\ 2s^2\ 2p^6\ 3s^1$; $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^5$; $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2$, etc. When first asked to make sense of, and represent, electronic structure in orbital terms, symbolism in this form may seem to be almost arbitrary to the learner (Taber, 2005). At university level, electronic configurations may be represented in terms of symbols representing electronic states rather than orbitals – (e.g. $(1s\sigma_g)^2$ $^1\Sigma_g^+$ for the ground state of molecular hydrogen). Special graphical diagrams may be introduced to represent both the electronic states and transitions.

Symbols Used to Represent Structure and Process in Organic Chemistry

Different fields within chemistry have developed their own specialist forms of symbolism. Organic chemistry uses a range of symbols in representations that learners need to make sense of. For example, minimal structural representation in organic chemistry (where structures may be extensive) uses a formalism that a line represents two carbon atomic centres joined by a single covalent bond, and saturated with hydrogen except where shown otherwise.

The naming system in organic chemistry includes numbers used to specify the positions of functional groups (propan-1-ol, propan-2-ol, hexa-2-ene, 1, 2-dichoroethane etc). New symbols such as *p-, o-, m-* (para-, ortho-, meta-), α-, β-, E/Z, D-/L-, (+)/(−), R-/S- etc. are introduced to distinguish isomers of more complex molecular structures.

A methyl group may be shown in a structural representation as CH_3 or Me, and similar pseudo-elemental symbols are used for ethyl, propyl and butyl side chains. It is common to represent a phenyl group as either Ph or as a hexagon with a circle inscribed within it. This circle is meant to represent electron density that lies above and beneath the main plane of the molecule. However, when faced with

Fig. 4.3 A representation of
the benzene ring
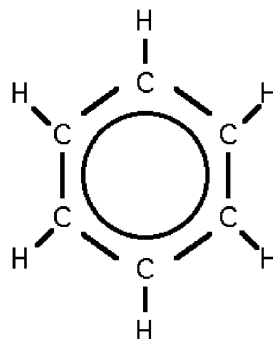
representations such as Fig. 4.3, learners may read symbolism that is not intended into the representation, such as suggesting the ring represents a repository inside the hexagon for 'spare' electrons.

The notion of spare electrons derives from reading the usual conventional representation of bonds, and the tetravalency of carbon,

> 'Students who have learnt that covalent bonding is a pair of electrons shared between two atoms represented by straight lines may not readily link the new symbol to bonding, but rather interpret it as standing for "spare" electrons *not* used in the bonding. Carbon is (in this interpretation) only explicitly shown as having three bonds, and so, students argue, there should also be "spare electrons". These are considered to be located "within the ring" or "left in the middle", and "you show that by the circle". So the circle was considered to represent the "six spare electrons in the middle." The definitions and modes of presenting bonds learnt at an earlier educational stage act as barrier to learning the new material: i.e. pedagogic learning impediments'.
>
> Taber, 2005: 107–108.

Another related aspect of conventional symbolism is the indication of a radical by using a single dot, such as Cl•. The • symbol represents an unpaired electron, and the presence of the other, paired, electrons is not made explicit. Again the symbolism relates to assumed shared knowledge: that the presence of an unpaired electron has particular consequences so needs signifying. Dots are also sometimes used in organic formulae, such as CH_3• CH_2• COOH (otherwise just represented as CH_3CH_2COOH). Again, this symbol has a different meaning depending upon context,

> "when a dot is used to break a formula into subunits, it may signify ignorance of how the subunits are structurally related, as in our inorganic example; or it may correspond to actual significant structural subunits, as in our organic example; or it may represent the combining ratios of the binary starting materials required for the synthesis of the compound, as in our phase diagram example."
>
> Jensen, 2006: 1590

Further symbols are used to indicate reaction mechanisms, in particular the use of curly arrows (to represent the movement of pairs of electrons) and 'fish-hooks' (to represent the movement of single electrons). Students need to understand the precise meaning of these arrows (which electrons move, and where from and where to) to appreciate how they represent stages in reaction mechanisms. Students who have been taught the formalism are not necessarily able to identify the outcome of

such symbolised electron movements, or to explain their thinking even when they do make a correct selection (Taber 2002a).

Ladhams Zieba (2004) reports that she found that when students were shown representations of reactants in nucleophilic substitution reactions, the relative position of the molecular representations seemed to influence the expected product of the reaction, and that representing the alkyl halide using a different form of structural formula led to students expecting a different type of reaction mechanism for the same reactants (this work is discussed in more detail in Bucat & Mocerino, this volume). This seems to be a case where a convenient informal convention commonly selected to represent the mechanisms (i.e. only showing stereochemical arrangements when they are significant) has been adopted as a cue to imply something not directly intended.

These examples suggest that the learner is not always aware which aspects of our use of symbolic representation in chemistry are intended to be significant. This is an area where further work would be useful, as clearly teachers need to do more to induct learners into the *intended symbolism* we use in teaching the subject. In the next section, these issues will be explored further in the particular context of learning about chemical equations.

Representing Chemical Equations

One of the central forms of representation in chemistry, and so in teaching and learning of chemistry, is the use of chemical equations. These are so ubiquitous, and again so familiar to the 'expert' (the chemist, the science teacher) that the abstract and complex nature of the representations, and so the learning challenges, may not be readily apparent.

Again we have a situation where the expert:

- has a level of familiarity with the formalism that enables her or him to automatically see past the symbols themselves;
- brings a wealth of background knowledge to the topic that helps 'make sense' of the representations beyond the information directly provided.

Consider the examples of some of the forms of 'chemical equations' (and related representations) met in school and college (i.e. middle and senior high school) science and chemistry classes that are shown in Table 4.1. For the purposes of this chapter 'half-equations' (Example 11) and symbolic representations of processes such as ionisation (Example 10) will be included under the generic heading of 'chemical equations'. Table 4.1 does *not* include examples of chemical reactions and reaction schemes that include structural formulae, as are commonly used in organic chemistry.

Table 4.1 Some examples of types of chemical equations met in learning chemistry

| 1	$2Mg + O_2 \rightarrow 2MgO$
2	$2NaOH_{(aq)} + H_2SO_{4(aq)} \rightarrow Na_2SO_{4(aq)} + 2H_2O_{(l)}$
3	$CaCO_3{}^{\Delta} \rightarrow CaO + CO_2 \uparrow$ [Δ should be above $\rightarrow$]
4	$AgNO_{3(aq)} + NaCl_{(aq)} \rightarrow AgCl_{(s)} \downarrow + NaNO_{3(aq)}$
5	$Ag^+{}_{(aq)} + Cl^-{}_{(aq)} \rightarrow AgCl \downarrow$
6	$N_2 + 3H_2 \Leftrightarrow 2NH_3$
7	$6CO_2 + 6H_2O \xrightarrow{h\nu} C_6H_{12}O_6 + 6O_2$ [$h\nu$ should be above $\rightarrow$]
8	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + energy$
9	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \Delta H = -890\,kJ\,mol^{-1}$
10	$Na \rightarrow Na^+ + e^- \quad \Delta H = 500\,kJ\,mol^{-1}$
11	$MnO_4{}^- + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O \qquad E^{\varnothing} = +1.52\,V$ [$^{\varnothing}$should be 'standard' symbol]
12	$[Cu(H_2O)_6]^{2+}{}_{(aq)} + 4Cl^-{}_{(aq)} \rightarrow [CuCl_4]^{2-}{}_{(aq)} + 6H_2O_{(l)}$

The Language of Chemical Equations

Representations such as these are routinely used to stand for chemical changes and processes that are the central phenomena in chemistry – they could be considered a fundamental part of the language for communicating chemistry. Just as in acquiring a language such as English, there is a need to both learn the symbols themselves, and the grammar of the language. As in English, there is an infinite number of possible permutations of symbols, some of which represent chemistry (as in the examples in Table 4.1), some of which are non-sense, and some of which follow the rules of grammar but do not reflect any known chemical processes. So an example such as

$$AgNO_{3(aq)} + 2O_2 + CO_2 + 2Mg \rightarrow Na_2SO_{4(aq)}$$
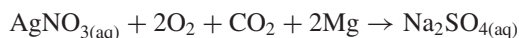
has the surface appearance of a chemical reaction, but does not follow the 'grammatical' rules of the chemical language (which are considered below). By comparison, an example such as

$$Pb + MgO \rightarrow PbO + Mg$$
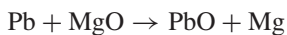
obeys the grammatical rules of the chemical equations genre, but represents a process that is not normally chemically feasible. The distinction has significance in that a student who seriously offered the first example as representing a possible chemical process lacks an appreciation of the most basic principles, whereas the second examples follows basic conservation principles, but does not reflect knowledge of specific chemical properties such as relative reactivity in this case. Similarly,

$$H_2SO_{4(aq)} + Fe_{(s)} \rightarrow FeSO_{2(s)} + H_2O_{2(l)}$$
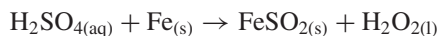
could be considered to represent an intermediate type of language error. Whereas the previous equation represents a common *type* of chemical reaction, but an unlikely example, this equation offers something that obeys the general grammar of the language, but does not make sense chemically.

We might compare here with a commonly quoted example the linguistic Chomsky used in discussing the grammar of the English language (Pinker, 1995). Chomsky pointed out that whilst the word strings 'furiously sleep ideas green colourless' and 'colourless green ideas sleep furiously' were both non-sensible, there was nevertheless a distinction as 'colourless green ideas sleep furiously' followed the grammatical rules of the language and would be recognised as such by English speakers even though it lacked semantic sense (cf. $H_2SO_{4(aq)} + Fe_{(s)} \rightarrow FeSO_{2(s)} + H_2O_{2(l)}$) whereas 'furiously sleep ideas green colourless' did not even offer the surface match with a sentence, despite comprising individual words that were all valid for use in the language (cf. $AgNO_{3(aq)} + 2O_2 + CO_2 + 2Mg \rightarrow Na_2SO_{4(a)}$).

By comparison with these flaws in the use of representation, the second of our three examples above ($Pb + MgO \rightarrow PbO + Mg$) contains valid 'words', and also obeys grammatical structure, yet is *still* not good chemistry. This example is analogous to a false statement in English, such as 'there are 12 days in a week', or 'the modern science of chemistry derived from the ancient art of tasseography'.

The purpose of drawing these comparisons is to highlight that – just as in learning a foreign language – there are several levels of skill needed for full competency in the language of chemical equations – and so several levels at which to potentially make mistakes.

Before they will be given credit for using the language in formal assessments, students must

- learn the allowed symbols and what they represent; *and*
- understand the grammar of the representational language; *and*
- know enough chemistry to be able to compose 'true' statements in the language, to represent actual or feasible reactions.

Each of these aspects offers challenges to learners.

Learning the Symbols

The 'words' of the chemical equation language are made up of symbols that stand for substances, such as Mg, MgO and O_2 in the first example in Table 4.1. These 'words' of course themselves comprise the 'letters' of the symbolic language, the symbols given to the chemical elements such as oxygen (O) and magnesium (Mg). In learning a language, the child spends a good deal of time familiarising him or herself with the symbols used to represent the sounds of the language, and the names given to those letter symbols. The language of chemical equations borrows those familiar script symbols, but the student of chemistry must remember the names of the common chemical elements, and whether they are represented by a single initial

(H for hydrogen), a two-letter code (Cl, but not Ch note, for chlorine), or even an 'irregular' label that does not match the learner's native language (so in English, Pb for lead, Na for sodium and so forth).

However, this comprises just the 'letters' of the language, and letters can be combined in arbitrary ways – HCl, HPb, OMg – only some of which link to meaningful words. The 'meaning' here being that the 'word' symbol relates to a compound of those 'letter' elements. There are 'spelling' rules to be learnt here as well: MgO not OMg, MgClCl (I will return to the use of numbers, below) not MgCl. The first of these rules requires us to order the elements according to electropositivity, a concept that is not usually taught until the student has met and been expected to learn a good many of the 'words' (formulae) that have to follow this rule. A rule of thumb that can be used at lower grade levels then is to put the metal before the non-metal, although this does not explain the 'spelling' in compounds such as $KMnO_4$ (rather than $MnKO_4$). The second 'spelling' rule links to the concept of valency, and is more significant, as although OMg is represented incorrectly only by convention, MgCl does not reflect a viable compound, and many chemical words (formulae) have 'homonyms' that signify *different substances*: NaO and NaNaO, HHO and HHOO, FeO and FeFeOOO, etc. Here it is essential to select the correct spelling (adding HHO and HHOO to a substance would likely give somewhat different outcomes!)

Of course, repeated letters are indicated in the language of chemical reactions by numerical subscripts, so that we have $MgCl_2$ rather than MgClCl, Na_2O (distinct from Na_2O_2, NaO_2), H_2O (and H_2O_2), Fe_2O_3 (and FeO) etc. Learners have to appreciate the distinction between these subscripts that 'balance' valency requirements in 'spelling the chemical words' and the numbers placed in front of 'words' (formulae) to balance up equations (discussed below). Superscript numbers may also appear when charges are represented, and so the superscript + and – symbols for ionic charge have to be appreciated. Also students will come across state symbols – (s), (l), (g), (m), (aq) – and symbols for gases evolved ($\uparrow$) and precipitates formed ($\downarrow$). Other key symbols indicate reactions ($\rightarrow$), equilibria ($\Leftrightarrow$,), conditions for reactions such as heat (Δ) and light (hν, or u.v. for ultraviolet), as in the examples given in Table 4.1.

Students will also come across equations that include energy as a term (Example 8 in Table 4.1), as well as those giving indications of energy changes (Example 9) or suggesting the magnitude of the energy change involved in a reaction or related process (Examples 10 and 11).

Learning the Basic Grammar of Chemical Equations

Chemical equations are used to represent chemical *processes* such as chemical reactions. A key feature then of a chemical equation is that it has two parts, representing 'before' and 'after' the process, separated by an arrow or other signifier of the process itself. Each of the examples in Table 4.1 has this structure.
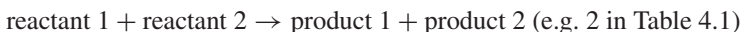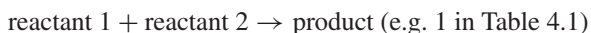
By convention, the left hand side of the equation represents before the process, and the right hand side represents what is present afterwards, and the arrow implies

'becomes' or 'changes into'. This convention is 'natural' for those brought-up with languages where script is read left to right – a convention that seems to be becoming universal. According to the on-line encyclopedia, Wikipedia (2007), the first Chinese edition of the journal 'Science' published in 1915 used the Western convention of left-to-right and top-to-bottom printing, which it justified to readers (more familiar with vertical writing, and reading columns right to left) in terms of the need to insert mathematical and chemical equations in the text!

Each side of a chemical equation may comprise several terms, usually separated by the '+' symbol. This indicates that what is present before and/or after the reaction or other process is best considered as comprising several discrete components. For a chemical equation representing a reaction, the different terms represent the chemical substances involved in the reaction, i.e.,
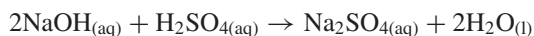
$$\text{reactant(s)} \rightarrow \text{product(s)}$$
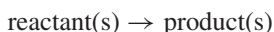
Clearly, there are a variety of possible permutations of the number of substances involved:

$$\text{reactant 1} + \text{reactant 2} \rightarrow \text{product (e.g. 1 in Table 4.1)}$$
$$\text{reactant 1} + \text{reactant 2} \rightarrow \text{product 1} + \text{product 2 (e.g. 2 in Table 4.1)}$$
$$\text{reactant} \rightarrow \text{product 1} + \text{product 2 (e.g. 3 in Table 4.1)}$$
$$\text{etc.}$$

Another key requirement of chemical equations (when presented in formulae, see below for consideration of word equations), is that they should be 'balanced'. This is considered further below, and relates to conservations that are expected during chemical processes (of matter, charge, energy).

Chemical equations may be presented both as words and formulae. Consider the second example in Table 4.1:

$$2NaOH_{(aq)} + H_2SO_{4(aq)} \rightarrow Na_2SO_{4(aq)} + 2H_2O_{(l)}$$

This could be written as:

$$\text{sodium hydroxide solution} + \text{sulphuric acid} \rightarrow \text{sodium sulphate solution} + \text{water}$$

Both of these forms of representation are 'symbolic' although words are more familiar symbols to students. Both of these forms present difficulties to learners. Although word equations may seem a more direct way for novices to represent chemical reactions, they may sometimes make more demands on learners. So, for example in completing equations, non-systematic names – such as ammonia – may not provide strong clues to the elements present, and there is a need to learn, recall and apply such rules as '-ate' implies oxygen present, etc.

Drawing on Background Knowledge to Interpret Symbolic Representations

One of the key messages of this chapter is that in chemistry we often use representations that are potentially ambiguous, but where the expert appreciates the intended symbolism by applying background knowledge according to contextual cues. For example, the symbol ∂ is commonly used in chemistry, but what does it represent? If the context is '∂ bond', then the symbol has a rather different meaning to if the context is '∂^+'.

A thought experiment was included earlier that illustrated how the complexity of a representation may appear very different depending upon the relative expertise of the perceiver within the relevant domain of knowledge. Consider the following task: Complete the following chemical equation:

$$\text{sulphuric acid} + \text{sodium hydroxide} \Rightarrow \text{_____} + \text{water}$$

This would seem a relatively trivial exercise for the expert. However, a student correctly answering the question does not just need to understand how the (word) equation represents a chemical reaction, and that the missing term is a substance produced when sulphuric acid reacts with sodium hydroxide. It is also necessary to be able to work out what that product is, which requires applying background knowledge. This may be actually 'knowing' the answer, or otherwise working it out by recognising this as a type of reaction (neutralisation); and comparing to a general scheme for that kind of reaction (acid plus alkali gives salt plus water); and recalling that if the alkali is sodium hydroxide the salt will be 'sodium something', and that sulphuric acid gives salts that are sulphates (Taber, 2002a). So producing the response 'sodium sulphate' requires *the coordination* of an understanding of the form of representation with specific chemical knowledge. When 160 Year 9 (13–14-year-old) UK students who had 'learnt' about chemical equations were set this question, a majority were able to answer it correctly – but only by the smallest margin. Only 81 (51%) worked out that the missing term was sodium sulphate (Taber & Bricheno, 2004).

Understanding What Is Signified by a Chemical Equation

For students to make sense of the basic grammar of chemical equations they need to appreciate the concept of the chemical reaction. This, in turn, requires an understanding of the notion of chemical substance. Although these are basic concepts in chemistry, they are known to present difficulties to many learners.

The notion of a pure chemical substance can be related to empirically identifiable properties (e.g. sharp melting and boiling temperatures) but is nowadays understood in theoretical terms that are abstract (Johnson, 2002; Taber, 2002a). So hydrogen, methane, diamond, sodium, sodium chloride and polythene – poly(ethene) – are all considered examples of single chemical substances, although they are very different

both in terms of molar properties and in terms of sub-microscopic structure. So for example, a definition that a pure substance contains only one type of molecule would not apply to the non-molecular materials, nor strictly to samples of polymers. Sodium chloride is considered a pure substance despite consisting of two distinct types of basic entity in the liquid state.

A chemical reaction involves a change in the substance(s) present, but in practice we distinguish chemical change from physical change in theoretical terms rather than in terms of observable properties. We know that the thermal decomposition of ammonium chloride is a chemical change, but the melting of ice is a physical change. We apply prior knowledge in terms of our sub-microscopic models of what is involved, not because there is obviously a different substance produced (to the novice observer the new materials produced in physical changes may look just as dramatic, even though chemically the same substance).

There are many examples of changes represented by chemical equations where an absolute distinction between a chemical and physical change is not helpful (Taber, 2002a). So Example 12 in Table 4.1 refers to a ligand-substitution that occurs without a dramatic energy change, but leads to a change in properties and (in terms of sub-microscopic models) involves the making and breaking of bonds, albeit relatively weak bonds. For many learners the scientific notion of a reaction is one that is difficult to acquire (Ahtee & Varjola, 1998).

An equation of the form

$$\text{reactant} \rightarrow \text{product 1} + \text{product 2}$$

could not represent a reaction for some learners. These students would exclude Example 3 from Table 4.1 as representing a reaction.

$$CaCO_3{}^\Delta \rightarrow CaO + CO_2 \uparrow \ [\Delta \text{ should be above } \rightarrow]$$
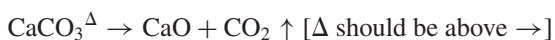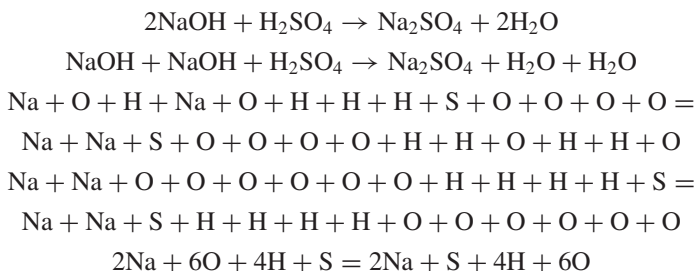
For these learners, this cannot be a *reaction* as the calcium carbonate is not reacting with anything! For others, this is considered to be a reaction, but only because heat is considered as a reactant on a similar basis to the carbonate. This reflects a common failure to discriminate objects from processes in science (Chi, 1992). This is a chemical reaction because new substances are produced, and the usual everyday meaning of 'reaction' (which has to be *to* something) acts as a potential barrier to appreciate the technical meaning of the term, a case where example of prior linguistic knowledge interferes with intended learning of science (Schmidt, 1991; Taber, 2005).

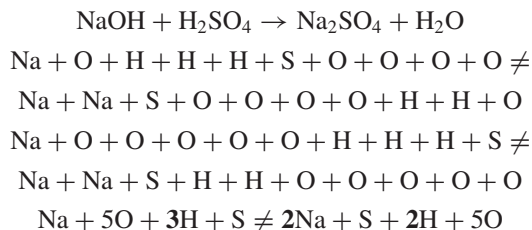## Conserving Matter in Reactions and Equations

A chemical equation has to be 'balanced' to give a full representation of a chemical change. This has both a principled and a pragmatic aspect. Consider the example (modified from Example 2 in Table 4.1):

$$NaOH_{(aq)} + H_2SO_{4(aq)} \rightarrow Na_2SO_{4(aq)} + H_2O_{(l)}$$
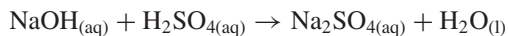
The pragmatic consideration is that if a student were to undertake this reaction, then it would be important to react corresponding 'amounts' of the two reactants. 'Amount' here implies the number of moles, and the unbalanced version of the equation would imply that equal volumes of reactant solutions (if the same concentration) were needed, when actually twice as much alkali solution would be needed as acid solution because the acid is dibasic. The principled point is that the equation represents a chemical process, which is subject to the constraints of conservation rules: matter (as energy) is conserved. In a chemical change, the elements 'present' (whether as elements or in compounds), must be conserved. A balanced equation has the same elements in the quantities represented on both sides:

$$2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$$
$$NaOH + NaOH + H_2SO_4 \rightarrow Na_2SO_4 + H_2O + H_2O$$
$$Na + O + H + Na + O + H + H + H + S + O + O + O + O =$$
$$Na + Na + S + O + O + O + O + H + H + O + H + H + O$$
$$Na + Na + O + O + O + O + O + O + H + H + H + H + S =$$
$$Na + Na + S + H + H + H + H + O + O + O + O + O + O$$
$$2Na + 6O + 4H + S = 2Na + S + 4H + 6O$$

whereas

$$NaOH + H_2SO_4 \rightarrow Na_2SO_4 + H_2O$$
$$Na + O + H + H + H + S + O + O + O + O \neq$$
$$Na + Na + S + O + O + O + O + H + H + O$$
$$Na + O + O + O + O + O + H + H + H + S \neq$$
$$Na + Na + S + H + H + O + O + O + O + O$$
$$Na + 5O + \mathbf{3H} + S \neq \mathbf{2Na} + S + \mathbf{2H} + 5O$$

The unbalanced version of the equation would imply that atoms have been created and destroyed (or transmuted) in the process: in contradiction to one of the fundamental principles of chemistry.

In the version of this equation included in Table 4.1,

$$2NaOH_{(aq)} + H_2SO_{4(aq)} \rightarrow Na_2SO_{4(aq)} + 2H_2O_{(l)}$$
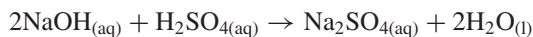
where state symbols indicate the states of the reactants, it may seem superfluous indicating the water produced. If we wrote this equation as

$$2NaOH_{(aq)} + H_2SO_{4(aq)} \rightarrow Na_2SO_{4(aq)}$$

then it could be argued that as '(aq)' implies water being present as a solvent, and as the water produced in the reaction effectively dilutes the solution (being no different from the water already present) it could be considered to already be included as part of '$Na_2SO_{4(aq)}$'. So from this perspective, the shorter form of the equation would be an acceptable representation of the chemistry. However, by convention we explicitly show the water as a discrete product.

This issue, once again, highlights why learning the symbolic language of chemistry presents challenges to students. The longer version of the equation is preferred, and this version offers an explicit representation of the conservation of matter that is fundamental to appreciating chemical processes. However, unlike the ('wrong') shorter version, this equation could be seen to imply that product water obtained in the reaction is somehow different to the solvent water already present in the mixture. This is not a trivial point when studies of learners' understanding of chemistry suggest that students may assume the origins of chemical species to be significant (Taber, 1998). Given the strength of such intuitions, our symbolic conventions may readily trigger or reinforce alternative conceptions (Taber, 2007).

Representing Energy Changes: An Additional Complication

Apart from conservation of matter, energy is also considered to be conserved in chemical processes. Chemical reactions usually involve some conversion of energy: for example in an exothermic reaction chemical potential energy is 'released' often as heat. Where this is considered significant, the magnitude of the energy released may be indicated by quoting the enthalpy value. Enthalpy is normally symbolised as H, and an exothermic enthalpy change is by convention negative, i.e. $\Delta H < 0$. So in Example 9 of Table 4.1, the combustion of methane is shown to release (under standard conditions at least), 890 kJ of energy per mole of reaction. Again by a convention, this means *per mole of methane* combusted, and NOT per mole of oxygen reacted.

Students may view the $\Delta H < 0$ for exothermic reactions convention as counter-intuitive, as they might more naturally associate energy 'released' with a positive signifier: i.e. negative (a loss) means we had to put energy in, and positive (a gain) means we got some out. The convention is unproblematic from a scientific perspective, but again the novice has not yet acquired the mental frameworks to support that way of thinking.

Energy is one of the most fundamental concepts in science, yet it is extremely abstract and has no ready definition that makes sense to students (Feynman, 1967). It is known that learners bring to class their own everyday (Solomon, 1992) and other alternative conceptions of the notion (Watts, 1983); and despite much debate in the educational literature (e.g. Driver & Millar, 1986), it is recognised that teaching a scientifically valid conception of energy remains a challenge for teachers (Grevatt, Gilbert, & Newberry, 2007). For example, in lower secondary education in England teachers are advised to discriminate between two teaching models of energy

concerning energy transfer and energy transformation (DfES, 2003). In our chemical example, the combustion could be described in terms of the *transformation* of chemical potential energy, through the process of heating (e.g. by the emission of electro magnetic (e-m) radiation) to internal energy; or as energy *transferred* from the reactants to the products and their wider surroundings. It is clear that this is a process that has no simple end-point (the surroundings being ultimately the Universe!) and is difficult to visualise for students. The 'initial' form of the energy is to be understood in terms of the configurations of charges within molecules, and the 'final' form is understood in terms of the kinetic and potential energy of molecules (or just kinetic energy, in a gas).

Other examples in Table 4.1 offer additional complications. Example 11 provides an electrode potential, which is related to, but not the same as, an energy change. Example 10 represents an endothermic process ($\Delta H > 0$). Both these examples include terms that should not be found in chemical equations representing reactions.

Another Complication: Sometimes We Have to Balance Charge as Well

Example 11 includes 'free' electrons. These are needed to balance the equation electrically:

$$MnO_4^- + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O$$
$$(-1) + 8(1+) + 5(-1) = (+2) + 4(0)$$
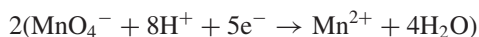$$-1 + 8 - 5 = +2$$
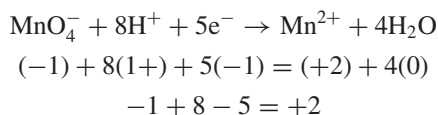
Just as mass and energy must be conserved, so also must electrical charge. Yet free electrons are not found stable in nature under the conditions of chemistry on earth, so cannot appear as reactants or products in representations of chemical reactions. Example 11 is a 'half-equation', something that represents a common pattern in chemical reactions, but only occurs when coupled to another suitable 'half-equation' (i.e., this reduction process must be paired with an oxidation process that 'releases' electrons), e.g.

$$2Br^- \rightarrow Br_2 + 2e^-$$

The student is expected to appreciate that the presence of a term that does not relate to a substance ('$2e^-$') shows that this particular equation *cannot* stand for a chemical reaction. (The student is also expected not to confuse superscripts used to denote charge with those showing mass numbers of isotopes.)
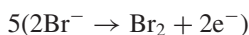
When coupled with a suitable matching half-equation, the 'electron accountancy' will remove the inadmissible term, For example:
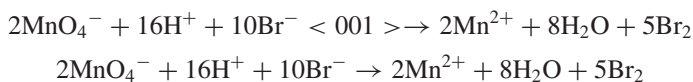
$$2(MnO_4^- + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O)$$

gives

$$2MnO_4^- + 16H^+ + 10e^- \rightarrow 2Mn^{2+} + 8H_2O$$

and

$$5(2Br^- \rightarrow Br_2 + 2e^-)$$

gives

$$10Br^- \rightarrow 5Br_2 + 10e^-)$$

and adding the reactant and product terms gives:

$$2MnO_4^- + 16H^+ + 10Br^- < 001 >\rightarrow 2Mn^{2+} + 8H_2O + 5Br_2$$
$$2MnO_4^- + 16H^+ + 10Br^- \rightarrow 2Mn^{2+} + 8H_2O + 5Br_2$$

Students at senior high school/college level are expected to be able to undertake this type of manipulation of symbols to produce balanced equations from half equations (whilst also adding the electrode potentials to check if the reaction is feasible). The resultant equation balances in terms of both the quantity of each element represented (2Mn, 8O, 16H, 10Br) and in terms of overall charge ($-2 + 16 - 10 = +4$).

However, just as real reactions do not include free electrons as reactants or products, they do not occur between or produce materials with (substantive) net charges. So whilst the equation above does *represent* the oxidation of bromide by acidified permanganate, it is an abstraction from a real chemical reaction where the bromide and the permanganate would be part of real substances that were (substantially) neutral. For example:

$$2KMnO_4 + 16HCl + 10NaBr \rightarrow 2MnCl_2 + 8H_2O + 5Br_2 + 10NaCl + 2KCl$$

This lengthier equation does a better job of describing the; reactants used in the chemical reaction: however, the potassium, chloride and sodium ions are not essential to the process and could in principle be substituted without changing the reaction in any meaningful sense. Indeed, as the products are all present in the same flask at the end of the reaction, as an aqueous solution, it is actually misleading to imply that some chloride ions are part of sodium chloride, and others part of potassium chloride: these solvated ions will be constantly colliding, forming transient complexes and disaggregating again. This is perhaps seen more clearly in comparing Examples 4 and 5 from Table 4.1. Equation 4 represents the precipitation of silver chloride from an aqueous solution of a chloride.

$$AgNO_{3(aq)} + NaCl_{(aq)} \rightarrow AgCl_{(aq)} \downarrow + NaNO_{3(aq)}$$
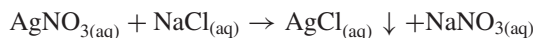
However, the reactants are present as solutions, and once mixed do not in any real sense contain silver nitrate and sodium chloride as separate substances (even in the hypothetical instant before precipitation occurs). Example 4 might best be rewritten as:

$$Ag^+_{(aq)} + NO^-_{3\ (aq)} + Na^+_{(aq)} + Cl^-_{(aq)} \rightarrow AgCl_{(aq)} \downarrow + Na^+_{(aq)} + NO^-_{3\ (aq)}$$
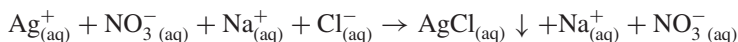
However, it is clear here that two of the ions are just 'spectators' that have no influence of the reaction, and could best be removed to give:

$$Ag^+_{\ (aq)} + Cl^-_{\ (aq)} \rightarrow AgCl_{(aq)} \downarrow$$
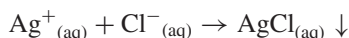
Thus we have Example 5 from Table 4.1. Equation 4 gives a better description of the overall reaction, but equation 5 highlights the essential chemical process, and can also stand for the parallel reactions where sodium chloride is replaced by potassium chloride, or any other soluble chloride. The chemistry student is expected to appreciate how both equations 4 and 5 can represent the same chemical processes.

The other example of an equation in Table 4.1 which includes a free electron is Example 10, which shows the process of ionisation of a sodium atom:

$$Na \rightarrow Na^+ + e^-$$

Again students are expected to realise that this does not represent a stand-alone chemical process, and electrons are not found free under usual conditions, and so this process would need to be coupled with one that provides a place for the electron to go. Students may meet this process as part of a simple redox process (say with the reduction of a less reactive metal), or as one component of the analysis of a more complex process using Hess's law to find an enthalpy change by aggregating the enthalpy terms of an indirect route.

However, in a different context, the student will be expected to accept this 'non-chemical' process as a phenomenon to be explored in is own right in chemistry, as senior high school/college students learn about patterns in ionisation energies. Although the oxidation of sodium atoms does not occur as an isolated event under normal (i.e. 'chemical') conditions, it can be facilitated in more extreme circumstances to measure the energy change. So in this topic, this equation effectively has a different status, moving from only representing a hypothetical process to standing for a real phenomena, albeit one that may be better considered physical, than chemical (Taber, 2003b). The endothermic nature of this process (the positive ΔH value in Table 4.1) implies that this is not something that can happen without an energy input. (Strictly speaking, the free energy change, ΔG, should be considered.) However, by the stage that students study ionisation energies a good many have adopted the octet rule as a general explanatory principle and expect a process that produces a species with a full outer shell to occur spontaneously (Taber, 1998). Indeed many students will interpret representations of even the most chemically dubious processes as feasible if they seem to produce outer shells that are full or

have octets of electrons (sometimes, but not away the same thing). So it is common for students to judge such unlikely chemical species as:

$$Na^{7-} \text{ and } Cl^{17-}$$

as being stable, as they tend to interpret the representation only in terms of the outer shell configuration and do not seem to consider the high charges, nor the failure to come across these examples in class; nor even such basic chemical patterns as metals tending to form cations!

Representing Equilibria: More Complexity

Most of the examples of chemical equations presented in Table 4.1 include an arrow ('→') symbol. This implies a direction to the chemical change represented: this is a process of reactant(s) becoming product(s). However, sometimes students meet reactions where an equality sign (=) or a double-headed arrow symbol (⇔, ⇌) is used. Students at secondary level will be introduced to the notion that some chemical reactions 'do not go to completion' or 'are equilibria'. A common introductory example met at this level is the reaction to produce ammonia (as in the Haber process),

$$N_2 + 3H_2 \Leftrightarrow 2NH_3$$
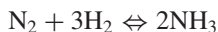
The simple (over) interpretation a student might make here is that there are reactants (the substances on the left hand side), and a product (in the right hand side) but some of the reactants do not react.

A more sophisticated understanding is linked to an appreciation of the interaction of thermodynamic and kinetic considerations and is likely to be dependent upon the ability to visualise some form of mental model involving molecular collisions and interactions (Gilbert, 2005). This allows the student to see that two reactions are occurring simultaneously:

$$N_2 + 3H_2 \rightarrow 2NH_3$$
$$2NH_3 \rightarrow N_2 + 3H_2$$
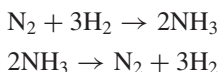
and that the overall process is a dynamic equilibrium. This is clearly quite an abstract idea being represented, where learning difficulties are common (Bannerjee, 1991), and a partial understanding can lead the student to conclude either that

- there must be equal amounts of reactants and products present (as both reactions are occurring simultaneously); or
- given enough time the reaction will go to completion unless reactants and products are energetically equivalent (as otherwise there will be more 'driving force' for one of the two reactions).

To move beyond this type of thinking requires the ability to coordinate different ideas in a 'systems thinking' manner that is not typical of many secondary level learners (Driver, Leach, Millar, & Scott, 1996). So at this level it may be considered sufficient to introduce the idea of equilibria and a few examples, almost as an 'advanced organiser' for later study.

Ultimately, the aim is that students should consider all reactions as in principle reversible, and so 'going to completion' is just a 'first approximation' for those reactions with large free energy values. Yet doing this by identifying a small number of 'equilibrium' reactions might be a high-risk approach. The symbolism used in introductory courses sets up a *false dichotomy* between irreversible (signified $\Leftrightarrow$) and reversible (signified $\rightarrow$) reactions. Whilst this may seem good pedagogy, moving from a simple model to a more complex one (as in metal/non-metal to the electronegativity scale), it can also act as a pedagogic learning impediment, when students have difficulty moving beyond the teaching model of covalent/ionic bonding as a dichotomy to appreciate polar bonds as something other than exceptions or a subset of covalent bonds (Taber, 1998).

A Comment on Dialects and Pidgins

If chemistry has its own language, then like all languages there will be 'regional' variations. For those who have become fluent, this variation will seem of minor significance. But for the novice, it may be much harder to distinguish whether a slightly different symbol is intended to imply a difference in the signified. Just as a student might be confused by moving between teachers who label the same electron shell as 'outer' and 'valence', respectively, it is unhelpful if the symbol ^2H becomes substituted by ^2D in a different classroom, or one teacher writes ^{235}U and another U^{235}. This is not a purely academic point because there may certainly be different dialects at work when adjacent knowledge domains share subject matter. So ^{235}U may usually refer to *an atom* in chemistry, but it is more likely to refer just to *the nuclide* in physics. As another example, if the $\rightarrow$ symbol has a different meaning to the $\Leftrightarrow$ symbol, then a student seeing an equation with a 1 symbol needs to decide whether this should be understood to mean something different again. This is not an obscure consideration when it has been suggested by IUPAC that '$\rightarrow$' (open arrow head) should mean something different to '$\rightarrow$' (closed arrow head) i.e. depending upon whether a reaction is considered to proceed in a single step (Laidler, 1981)!

When a technical language is adopted by those who do not share the expertise of its parent community, it may actually become distorted, and this may make it even more difficult for students to keep clear what different forms of symbolism mean. So in biology lessons students are likely to meet equations representing photosynthesis and aerobic respiration (Examples 7 and 8 in Table 4.1). When just considering the substances involved, these two equations will seem to stand in the same relation as those discussed for the hydrogen/nitrogen–ammonia equilibrium:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$
$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$
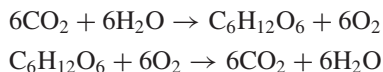
This would ignore the conditions of the two reactions, and in particular the special circumstances under which the endothermic photosynthesis reaction takes place. This also ignores how multi-stage reactions are being summarised in a single equation. It is not unusual to see energy included as a term, especially in the respiration equation:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + energy$$

In chemistry we usually indicate the energetics of equations separately from the equation itself (as in Example 9 in Table 4.1), but if energy is included as a term, *especially in a word equation*, this can undermine the significant distinction between what is happening in a chemical reaction in terms of matter and energy.

$$glucose + oxygen \rightarrow carbon\ dioxide + water + energy$$

Despite the common inclusion of energy terms in these equations it is not unusual for students to consider that they both represent ways in which the plant *obtains* its energy. Indeed it is common for students to assume an incorrect temporal symmetry (the plant obtains energy in the day by photosynthesis, and at night when it is dark by respiration, e.g. Sanders, 1993), whilst failing to appreciate that the symmetry represented in reactions 7 and 8 *should imply* that if one process *releases* energy the other must *require* it.

The Symbolic Level as a Mediator Between the Macroscopic and Sub-microscopic Levels

At the start of this chapter it was suggested that often in chemistry (and in teaching and learning chemistry) the symbolic level mediates between the macroscopic and sub-microscopic levels. To appreciate this notion of the symbolic level mediating the macroscopic and molecular levels it is useful to reiterate the role of sub-microscopic level in relation to the macroscopic level. One of the key features of modern chemistry is that much of explanatory theory used to systemise the subject is based upon models of the interactions between the particles that materials are conjectured to be composed of. The term particle is itself misleading for some younger students, who have been shown to consider that grains of salt or sugar are the particles that their teachers refer to, rather than hypothetical particles at a considerably smaller scale. The particles of the sub-microscopic level are molecules, ions, electrons etc. that exist at a scale so minute that quantum effects (that are largely negligible for particles of directly observable scale) become highly significant. Indeed, it is the way these 'quanticles' have properties so very different from more familiar macroscopic

particles that offers much of the power of particle models in explaining chemistry. Quanticles are not hard impenetrable entities with sharp edges, but rather fuzzy fields with properties modelled by quantum rules.

In effect the chemist, and chemistry teacher, *explains* the observed chemical behaviour of matter (substances) – colour changes, precipitation from solution, characteristic flame colours, etc. – *in terms of the very different* behaviour of the quanticles that are considered to form the materials at the sub-microscopic level. Much of this involves the reconfiguration of systems of negative electrons and positively charged atomic cores (or 'kernels') due to electrical interactions constrained by the allowed quantum states.

It is known that the use of this type of sub-microscopic explanatory model is very challenging to many learners (Harrison & Treagust, 2002). Indeed, failing to fully appreciate the way quanticles have different properties to familiar particles, students commonly adopt a type of pseudo-explanation where they 'explain' the properties of bulk matter in terms of the properties to be explained being properties of the atoms or molecules of which the bulk material is composed. This is represented in Fig. 4.4 which illustrates the tautological nature of these kinds of pseudo-explanations: they can only explain the properties *if* we just accept that the quanticles have these very properties.

This misses the very point about our particle models offering genuine and extensive explanatory value in science. There is perhaps a link here with the limitation of secondary and college level students' typical level of appreciation of the nature of models in science and of scientific explanation (Grosslight, Unger, Jay, & Smith, 1991; Driver et al., 1996; Gilbert, Taber, & Watts, 2001). Even University students may not have developed the mental models needed to facilitate effective thinking about the sub-microscopic world (Chittleborough, Treagust, & Mocerino, 2002).

So the particles making up materials are considered to be hard or soft, hotter or colder, sharp, conducting, square etc. As one journal article (Ben-Zvi, Eylon, & Silberstein, 1986) asked rhetorically: can an atom of copper be malleable?
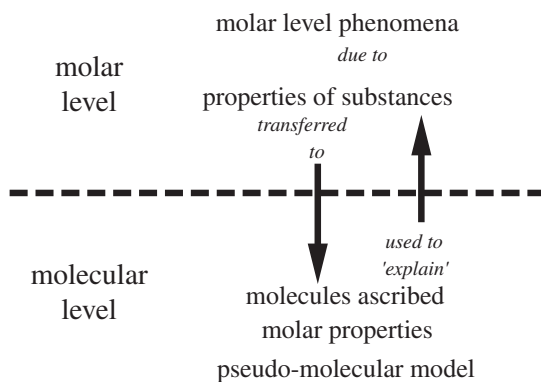

molar level phenomena
due to

molar level

properties of substances
transferred
to

molecular level

used to
'explain'

molecules ascribed
molar properties

pseudo-molecular model

Fig. 4.4 How learners misapply particle models (from Taber, 2000b; previously published in Taber, 2001b)

Given this context, the use of chemical symbols, formulae and equations can be readily misinterpreted in the classroom, because often the same representations can stand for both the macroscopic and sub-microscopic levels. So H could stand for an atom, or the element hydrogen in an abstract sense; H_2 could mean a molecule or the substance. One common convention is that a chemical equation represents molar quantities, so in Example 9 in Table 4.1,

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
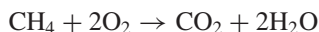
the enthalpy change was indicated in kilojoules per mole (again symbolised, here as kJ mol^{-1}, but sometimes shown as kJ/mol). So this tells us that when one mole of methane reacts with two moles of oxygen to give a mole of carbon dioxide and two moles of water vapour, 890 000 joules of energy will be 'released' (i.e. transformed). However, as the formula CH_4 can also indicate a molecule of methane (and similarly with O_2, CO_2, H_2O), the teacher can use the equation to *represent either* a change in substances at the macroscopic level, *or* the particles interacting and produced at the sub-microscopic level.

This provides a very strong tool for communicating explanations, as the teacher can move between discussing the bench phenomena and the (sub-microscopic) explanatory models readily. By presenting an equation that describes the reaction (a macroscopic phenomena that students can see etc.) in a form that directly links to the molecules or other quanticles (ions, etc.) considered to be present at the sub-microscopic level, the symbolic representation acts as a referent to both levels and so *at a meta-level also represents the relationship and mapping between substances and quanticles*.

Whilst this is a powerful tool, once again it means that the learner has to deal with ambiguity in our symbolic representation, and to draw upon context and background knowledge to interpret when the teaching is using the symbolic representation to stand for phenomena, and when it models the conjectured world of subatomic particles used in chemical explanations. Such interpretation is automatically undertaken by an expert (with high familiarity with the symbolic language and extensive background knowledge), but this again adds to the cognitive load on a novice learner trying to follow a lecture or classroom presentation.

Our verbal labels have the same ambiguity. When the teacher talks of hydrogen or oxygen she may be talking about the element (as a theoretical entity that is in some sense conserved in reactions although being incorporated in different compounds); the substance; or an atom or molecule:

- Ethene contains less hydrogen than ethane
- Hydrogen burns with a squeaky pop
- Hydrogen has one electron in a 1s orbital
- Hydrogen contains a pure covalent bond

In these four sentences we see the same word, 'hydrogen', used as a label to represent four different entities. Of course these four versions of 'hydrogen' are clearly related, but making the correct sense of any sentence using the word requires the

learner to realise whether it is the element, the substance, the atom or the molecule that is signified.

The lack of precision, indeed ambiguity, of our symbol system (words, formulae and equations) offers a fluidity that provides ready shifts between the different levels at which we discuss chemistry: but whilst the particular meaning at any one moment seems obvious to the expert, such shifts *need to be carefully signalled* for learners to follow them. There is a potentially vicious circle here. For those students who do not appreciate how the quanticles that populate the sub-microscopic realm have distinct properties from matter in bulk, the contextual information that may signify shifts between these two levels will not cue the shift. So statements (e.g. 'copper is a good conductor') may be interpreted at the wrong level, which may *reinforce* existing inappropriate thinking about chemistry at the sub-microscopic level.

Teaching Chemistry with the Symbolic Level of Representation

It would clearly be possible to multiply the examples used in this chapter many times over, for the symbolic level of representation provides a basic language for discussing, teaching and learning chemistry, and so is ubiquitous in the discipline of chemistry and in chemistry classrooms. When teaching the symbolic conventions of chemistry it is important for the teacher to appreciate how it is likely to take time, and practice, before mastery of the new language is possible. As this chapter has suggested, this is especially so in the context of a subject like chemistry. It is one thing to teach a learner a foreign language that has similar grammar to the native language, and where the new vocabulary generally refers to the familiar and understood. This can be difficult enough for many students, even though they are able to construct new knowledge on sound foundations. However, as shown above, the symbols and grammar of the language of chemistry are closely tied to its basic conceptual principles, and so the language of chemistry has to be constructed on an abstract and less familiar knowledge base.

Indeed, learners of chemistry are likely to be learning to develop fluency in the language of chemistry *as* they learn the subject through the language. Given that chemistry has its fair share of abstract concepts – electronegativity, valency, isomerism, etc. – and principles – conservation of 'elements', but not actual elements, in chemical reactions (in the English usage at least, the French meaning of element is somewhat different, Cokelez, Dumon, & Taber, 2007) – it is not surprising that many students struggle in the subject. Not understanding the subtleties of the symbolic language makes it *difficult* to learn the ideas. Not understanding the ideas, or holding alternative conceptions for basic chemical concepts, makes it *easy to misinterpret* what is represented through the language.

That said, many students are successful in the subject – somehow coordinating, developing and understanding of the ideas and increasing fluency in the language into a virtuous circle. Perhaps more detailed research into exactly how this is achieved is indicated. This is one area where longitudinal case studies of individual

learners could be very informative, giving insight into the complexity of evolving conceptual ecologies, and the factors that support and impede learning in particular teaching contexts (Taber, 2006).

Earlier a quick tour of some of the symbols used to represent chemistry in teaching and learning the subject was offered. The symbols are not just labels for words, but closely linked to concepts, which may themselves offer considerable challenge to learners. These concepts may relate to the molar or sub-microscopic levels, and as we have seen the same label ('hydrogen') often actually signifies several related concepts that bridge these levels. It seems clear that learners will be assisted in learning the symbolic language of chemistry if the introduction of the symbol system is both carefully sequenced and suitably paced (where 'suitable' is judged at the learner's resolution). Yet the introduction, and consolidation of chemical symbols cannot sensibly be divorced from the concepts being represented, where the problems of planning teaching to scaffold student learning are well recognised (e.g. Jensen, 1998; Johnstone, 2000; Taber, 2001b; Nelson, 2002).

In practice, this 'layering' of complexity occurs on several fronts:

- in considering materials, in moving from distinguishing pure substances from mixtures, to the distinction between elements and compounds;
- in moving from a general particle model to thinking about atoms, molecule, and ions, and then to electronic structures;
- from thinking of substances to processes to dynamic equilibria;
- from simple reactions to multi-step reactions;
- from thinking of matter, to matter-plus-charge, to matter-plus-charge-plus-energy.

Teachers will need to plan progression in learning across such different fronts and as we have seen the symbol systems used accrue with the additional detail and complexity that needs to be represented. In the meantime, the analysis presented in this chapter suggests that teachers should bear in mind some key general points:

- be aware that learners will chunk chemical symbols less effectively than experts;
- be aware of the way the use of symbolic representations may increase the perceived complexity, and so the cognitive demand of a task;
- always consider whether the symbols used are ambiguous, and if so be explicit about which meaning is intended at any point (element, atom, substance, molecule, etc.);
- be careful to be consistent in the use of symbols, and in not mixing matter and energy terms in equations;
- always clearly signpost when mediating a shift between macroscopic and sub-microscopic levels through symbolic representations: e.g. 'now this equation also represents. . .'

Whilst further empirical research is indicated to explore what types of teaching schemes might best support student learning, it *is clear* that teachers should bear in mind the need to support progression between increasing levels of complexity, both (i) by allowing students sufficient opportunities to consolidate one layer of

symbolism before introducing the next, and (ii) by making explicit the differences and links between the different sets of symbols.

The symbolic language of chemistry is an intellectual achievement of great power: but like all such systems it is only of value to us once we are fully initiated so it can become a facilitator of quick and effective communication, rather than being an additional barrier to comprehension and understanding. Like any complex material to be learned, it needs to be introduced in non-threatening ways – in digestible learning quanta, supported by effective scaffolding – and reinforced and applied in a wide range of examples and contexts until it becomes fully consolidated in memory. Only then can it be considered suitably robust prior knowledge to have moved from being part of what is to be mastered, to providing sound foundations for supporting further learning.

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