Introduction: Macro, Submicro and Symbolic Representations and the Relationship Between Them: Key Models in Chemical Education

John K. Gilbert and David F. Treagust

The Facets of Chemical Literacy

We live in a complex, rapidly changing, material world, major aspects of which require an understanding of the ideas of chemistry. Education for ‘scientific literacy’ in respect of ‘the public’ – people of all ages – is now widely seen as a general goal for science education, whether pursued formally or informally. It seems appropriate to talk about ‘chemical literacy’ – the contribution that chemistry can make to scientific literacy – and to amend the hitherto general discussions to focus on this particular aspect (Laugksch, 2000; Roberts, 2007).

Expressed in the broadest terms, acquiring chemical literacy might involve (after DeBoer, 2000):

Learning the chemistry that has direct application in everyday life; for example, understanding why stain-removers work in particular contexts;
Learning about chemistry as a cultural force in the modern world; for example, about how the emergence of chemistry has enabled us to explain the effectiveness of successful medicines;
Learning the chemistry that enables a person to become a more informed citizen; for example, to be able to discuss the use of sustainable energy sources in a rational way;
Learning the chemistry that enables a person to understand reports of and discussions about chemistry appearing in the media; for example, being able to understand why accidents in nuclear plants have high risks;
Appreciating the role of chemistry in the world of work; for example, that the range of building materials has been greatly expanded (e.g. plastics) since the advent of chemistry;
Learning about chemistry as a particular way of examining the natural world; for example, being able to appreciate why warm salt water produces rust on iron objects;

J.K. Gilbert (✉)
The University of Reading, Reading, Wokingham RG6 6FN, UK
e-mail: j.k.gilbert@reading.ac.uk

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Being able to communicate – to read and write – about chemistry. Today, communication at world level is based on texts and images. Being able to effectively communicate using the special vocabulary of chemistry enables a person to have access to that sphere of knowledge;

Learning chemistry for its aesthetic appeal; for example, being able to appreciate the beauty of natural crystals;

Becoming more sympathetic to chemistry as a field of scientific enquiry; for example, understanding that the field of genetics, with all its implications for the future, rests on chemical principles;

Learning about the nature of chemical technology and about its relation to chemistry; for example, understanding how aluminium is produced from alumina.

Put more prosaically, chemical literacy might, (after Shwartz, Ben-Zvi, & Hofstein, 2005), involve the following procedural competences:

Understanding the nature of chemistry, its norms and methods. That is, how chemists go about their work and how the products of that activity are accepted as scientific knowledge;

Understanding the key theories, concepts and models of chemistry. The subject rests on a very few widely applicable theories combined into models that have wide application and not on a large number of apparently isolated facts;

Understanding how chemistry and chemistry-based technologies relate to each other. Whilst chemistry seeks to produce explanations of the natural world, chemical technologies seek to change that world. The concepts and models produced by these two fields have a strong interrelation and therefore influence each other;

Appreciating the impact of chemistry and chemistry-related technologies on society. Understanding the nature of phenomena to which chemistry is applicable. Producing amendments to or variations on those phenomena both change how we see the natural world and the scope of our actions on it.

The Degrees of Chemical Literacy

However expressed, the agenda for chemical literacy is both lengthy and demanding. It is not reasonable to expect that most people will acquire chemical literacy to the same extent in respect of each of these goals and competences. We can therefore talk about *degrees* of chemical literacy. Using the ideas of Shwartz, Ben-Zvi, and Hofstein (2006), moving from the ‘lowest’ to the ‘highest’ levels of chemical literacy, these might be termed:

Practical or functional chemical literacy: that is needed for a person to function normally in respect of food, health and shelter in everyday life.

Civic literacy: that is needed for an informed debate about matters with a chemistry or a chemical technology-related dimension;

> Cultural chemical literacy: being able to appreciate chemistry as a major aspect of scientific endeavour. We must assume that this level implies an ability to enter into professional-level dialogue with a chemist.

The substance of chemistry as a field of scientific enquiry is made up of four components: the processes used to obtain (discover or create) chemical knowledge; the general concepts and specific facts so produced; the applications of that knowledge in understanding and changing the world; and the implications of that understanding and change for individuals and societies. Chemical education involves an introduction to a core of ideas. These ideas are that

- all matter is particulate in nature;
- the chemical elements display periodicity in their physical and chemical properties;
- compounds consist of two or more elements. In many cases this involves the creation of specific, directional chemical bonds which form when electrons pair;
- the constituents of compounds take on a distinctive geometric relationship to each other;
- energy is conserved as chemical reactions take place;
- the entropy of the universe (system plus environment) tends to increase during chemical reactions;
- there are energetic and geometric barriers to chemical reaction;
- there are only four ‘types’ of chemical reaction, the transfer of a proton, the transfer of an electron, the sharing of electrons and the sharing of electron pairs (Atkins, 2005).

Understanding these ideas – to whatever degree – involves mentally engaging with *representations* of them and the phenomena to which they relate. The notion of representation is not an easy one. Perhaps every chemistry course should begin by showing the famous painting by the Belgian Surrealist painter René Magritte, with its inscription *Ceci n’est pas une pipe* (French for *This is not a pipe*), currently housed at the Los Angeles County Museum of Art. The picture shows a pipe that looks as though it might come from a tobacco store advertisement. Magritte painted below the pipe: *“Ceci n’est pas une pipe” (This is not a pipe)*, which seems to be a contradiction but is actually true. The painting is not a pipe, but rather an *image* of a pipe (see http://en.wikipedia.org/wiki/The_Treachery_Of_Images). This is the essence of a representation that is discussed in chemistry. In one way or another, understanding each of the core elements may be described using three types of representation in which chemical ideas are expressed (Johnstone, 1982, 1991, 1993).

The Three Types of Representation in Chemistry

In summary, the first type of representation seeks to represent phenomena as experienced with the senses (or sense-extensions); the second seeks to support a qualitative explanation of those phenomena, whilst the third seeks to support a quantitative explanation of those phenomena. In somewhat more detail, the three types can be defined as follows.

The First or Phenomenological Type

When trying to understand and to manipulate matter and materials, chemistry does not start by looking at the natural world in all its complexity. Rather, it seeks to establish what have been termed *exemplar* phenomena: ideal or simplified examples that are capable of investigation with the tools available at the time (Gilbert, Boulter, & Elmer, 2000). This level consists of representations of the empirical properties of solids, liquids (taken to include solutions, especially aqueous solutions), colloids, gases and aerosols. These properties are perceptible in chemistry laboratories and in everyday life and are therefore able to be measured. Examples of such properties are mass, density, concentration, pH, temperature and osmotic pressure.

The Second or Model Type

Chemistry seeks to develop models for causal explanations of all the phenomena that fall within its remit. It is the characteristic of chemistry that this wide range of models involves entities that are too small to be seen using optical microscopes. In chemistry, it is usual to produce models built from entities such as atoms, ions, molecules and free radicals, for phenomena described with the first type of representation. For example, the occurrence of solids can be described in terms of packed atoms or molecules, or colloids as assemblies of entities into micells. Furthermore, to understand the material world in terms of changes in properties, models of the second type are concerned with the distribution of the electrons in any bonding within and between these entities. This may be done in terms of electron density distributions, or in terms of the shapes of atomic and molecular orbitals (including the use of valence electron repulsion theory). These descriptions may be given in the visual mode of representation, for example as diagrams or graphs (i.e. in two dimensions), or in the material mode, for example in space-filling or ball-and-stick form (i.e. in three dimensions; Gilbert et al., 2000).

The Third or Symbolic Type

This level involves the allocation of symbols to represent atoms, whether of one element or of linked groups of several elements; of signs to represent electrical charge; of subscripts to indicate the number of atoms in an individual ion or molecule; of letters to indicate the physical state of the entity (e.g. solid (s), liquid (l), gas (g), aqueous (aq) or other solution). This depiction is then followed by the inclusion of these representations as appropriate within all conventions of chemical and ionic equations, with the use of prefixed coefficients to show the conservation of matter during a reaction. This level of representation also can be used both in respect of the first, the phenomenological representational type, when dealing with bulk quantities of reactants and products in stoichiometric computations, and with a wide range of models of the second type of representation when describing physical changes (e.g. changes of state and dissolution of solutes) and the chemical changes taking place during reactions.

Representational Systems in Chemistry – Terms Used in the Chemical Education Literature

One of the major issues in developing a defendable approach to the teaching and learning of these three types has been the lack of a generally agreed terminology for them as is illustrated in the summary of the words/phrases used in the literature by some authors:

Table 1 Words/phrases used for the three 'levels' of representation

Authors	Terms used
(Andersson, 1986)	*macroscopic world* *atomic world*
(Ben-Zvi, Eylon, & Silberstein, 1987)	*macroscopic level* *microscopic level* *symbolic level*
(Gabel, Samuel, & Hunn, 1987) (Gabel, 1994)	*macroscopic level* *microscopic level* *symbolic level*
(Johnstone, 1991)	*macro level* *sub-micro level* *symbolic level*
(Bodner, 1992)	*macroscopic world of chemistry* *molecular world of chemistry* *symbolic world of chemistry*
(Johnstone, 1993)	*macrochemistry* *submicrochemistry* *representational chemistry*
(Fensham, 1994)	*macroscopic world* *atomic world*
(Nakhleh & Krajcik, 1994)	*macroscopic system* *microscopic system* *symbolic system* *algebraic system*
(Johnstone, 2000)	*macro* *submicro* *representational*
(Treagust, Chittleborough, & Mamiala, 2003)	*macroscopic* *submicroscopic* *symbolic*

A summary of the above shows various terms used for each type of representation: first (macro level, macroscopic level, macroscopic world), second (sub-micro level, microscopic level, submicro level, submicroscopic level, molecular world, atomic world), and third (symbolic level, symbolic world, representational chemistry, algebraic system). In our view, the system of terminology should be both as brief as possible and avoid any possible ambiguities of meaning. Consequently, 'sub-micro' and 'sub-microscopic' fall foul of our first criterion for they perhaps imply that such a level can be seen through an optical microscope. For those reasons, we have decided to use *macro, submicro, symbolic* for the individual types and *triplet relationship* to cover all three. The triplet relationship is a key model for chemical education. However, the authors in this book have been free to decide for themselves which conventions to use. *Nevertheless, it is our intention to promote the terms macro, submicro, symbolic in all subsequent work and to discuss the value of the triplet relationship in chemical education.*

Student's Problems in Understanding the Triplet Relationship

There is considerable evidence that chemistry students find the conventions of the triplet relationship difficult to understand and to use. These problems may be attributed to

(a) A lack of experience with the macro type. Suitable practical experience is either not provided for students (Nelson, 2002) or else students are unclear about what they are going to learn from it (Hodson, 1990).
(b) A range of misconceptions about the nature of the submicro type, based on confusions over the particulate nature of matter (Harrison & Treagust, 2002), and an inability to visualize entities when represented in that type (Tuckey & Selvaratnam, 1993).
(c) A lack of understanding of the complex conventions used in the symbolic type (Marais & Jordaan, 2000).
(d) An inability to move between the three types (Gabel, 1998, 1994).

The importance of the triplet relationship as a model for chemical education and the problems associated with it are the justification for this book, which examines them in more detail and discusses possible and proven ways of improving this vital area of learning in science.

The Aims and Structure of this Book

In order to discuss the nature and significance of the triplet relationship, this book is concerned with

1. The ways that the learning of the three types of representation, taken singly, can be supported;

2. The ways that an ability to mentally move between the three types of representation can be supported;
3. Approaches to the design of curricula that can facilitate more effective learning by students within this domain of chemical education.

This book is divided into four parts. In Part I, four chapters attempt to pin down the nature and origin of the challenges that are faced in teaching and learning about the triplet relationship. In Part II, the authors show how existing good practice can be implemented and report on some novel ways to improve upon that practice. In Part III, some radical approaches to addressing these challenges are presented. In Part IV, a single chapter attempts to synthesise the ideas that have been presented, discuss to what extent the problems have been addressed, and what is needed to actually bring about substantial and lasting change in chemical education in respect of the triplet relationship as a key component of chemical education.

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