John K. Gilbert
David Treagust
Editors

MODELS AND MODELING IN SCIENCE EDUCATION

Multiple Representations in Chemical Education

Springer

MULTIPLE REPRESENTATIONS IN CHEMICAL EDUCATION

Models and Modeling in Science Education

Volume 4

For other titles published in this series, go to
http://www.springer.com/series/6931

Multiple Representations in Chemical Education

John K. Gilbert
Editor

The University of Reading, UK

David Treagust
Editor

Curtin University of Technology, Science & Mathematics Education Centre, Australia

Springer

Editors

Prof. John K. Gilbert
1 Croswell Cottages, Goose Lane
Mayford
Woking, Surrey
1 Croswell Cottages, Mayford
United Kingdom GU22 0NW
j.k.gilbert@reading.ac.uk

Prof. David Treagust
Curtin University of Technology
Science & Mathematics
Education Centre
Perth WA 6001
Australia
d.f.treagust@curtin.edu.au

ISBN: 978-1-4020-8871-1 e-ISBN: 978-1-4020-8872-8

DOI 10.1007/978-1-4020-8872-8

Library of Congress Control Number: 2008940333

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Foreword

Many years ago, I went into my office carrying a tray of molecular models. My secretary asked what they were and I proceeded to explain that this one was salt, this one sugar and another represented diamond. She nodded sagely and then said, ‘I cannot see any connection with the real things. Why do you bother to use these pretty models?’ I had just returned from a tutorial with a group of undergraduates who had been ‘politely interested’ in the models, but had shown as little real enthusiasm and understanding as my secretary. This prompted me to question my own enthusiasms for molecular models and my apparent inability to transmit my vision of the mental liberation and satisfaction there was to be found in the use of models, both physical and mental.

This led to my little paper in School Science Review (Johnstone, 1982) and further thought resulted in my later publications (Johnstone, 1991, 1993, 2000) cited in the introduction of this present book. The triangle which I proposed had its origins in geology where mineral compositions were set out as combinations of silicon dioxide, magnesium oxide and calcium oxide. The corners represented the pure components, the sides represented binary combinations of any two components and the points inside represented combinations of all three. I had come to the conclusion that the three ‘components’ or ways of thinking about chemistry were often presented simultaneously (even in the same sentence) and would be represented by points inside the triangle. From the point of view of Information Processing, this had all the potential for overload for the learner. What was for me a beautiful, integrated view of chemistry had all the potential for confusion and non-learning. The practitioners could freely and unconsciously move from one type of thought to multiple combinations of all three, but had perhaps never thought of how they had acquired this facility.

My own introspection made me realise that, even at university, I had learned chemistry substantially through the macro and representational modes and only later did I meet the sub-micro. In my training in inorganic analytical chemistry, structure and molecular models hardy ever appeared. Organic chemistry study, which came later in the course, was when structure took on meaning for me. I had learned initially along one edge of the triangle before entering the centre. It might be salutary for readers to do some similar introspection to recapture some of the learning problems they themselves encountered and to find ways to enable their students to find easier paths to ‘enlightenment’.

I am happy to see suggestions for a curriculum development for all, beginning with the macro corner and progressing along the side linking to the sub-micro, made ‘tangible’ through physical and mental models.

I am pleased to welcome the publication of this book which has taken a serious look at this problem and explored ways to facilitate the processes which will enable learners to gain insights into the elegance, beauty and utility of the discipline without suffering the overload and mental constipation which bewilders and eventually repels those we are trying to attract.

University of Glasgow, Scotland Emeritus Alex Johnstone

References

Johnstone, A. H. (1982). Macro- and micro-chemistry. *School Science Review, 64*, 377–379.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning, 7*, 75–83.

Johnstone, A. H. (1993). The development of chemistry teaching: a changing response to a changing demand. *Journal of Chemical Education, 70*(9), 701–705.

Johnstone, A. H. (2000). Teaching of chemistry: Logical or psychological? *Chemical Education: Research and Practice in Europe, 1*(1), 9–15.

Contents

Part I The Challenges Faced in Teaching and Learning About the Representational Triplet

Part II Improving Existing Pedagogy in Respect of the Triplet Relationship

Part III Classroom Solutions to the Challenges Posed by the Triplet Relationship

Contributors

Wiebke Brockmeier University of Oldenburg, Oldenburg, Germany

Bob Bucat University of Western Australia, Crawley, WA 6009, Australia, bucat@chem.uwa.edu.au

Astrid M.W. Bulte Universiteit Utrecht, Utrecht, The Netherlands, A.M.W.Bulte@uu.nl

A.L. Chandrasegaran Curtin University of Technology, Perth, WA 6845, Australia, Chandrasegaran@curtin.edu.au

Maurice Cheng The University of Reading, Reading, Wokingham RG6 6FN, UK, mwcheng@hkucc.hku.hk

Lian Sai Chia Nanyang Technological University, Nanyang Avenue, Singapore

Gail Chittleborough Deakin University, Burwood, VIC 3125, Australia, Gail.Chittleborough@deakin.edu.au

Mei-Hung Chiu National Taiwan Normal University, Taiwan, Republic of China, mhchiu@ntnu.edu.tw

Bette Davidowitz University of Cape Town, Rondebosch 7701, South Africa, Bette.Davidowitz@uct.ac.za

Poliana F.M. Ferreira Federal University of Minas Gerais, Brazil

John K. Gilbert The University of Reading, Reading, Wokingham RG6 6FN, UK, j.k.gilbert@reading.ac.uk

Ngoh Khang Goh Nanyang Technological University, Nanyang Avenue, Singapore

Katarina S. Wissiak Grm University of Ljubljana, Ljubljana, Slovenia, Katarina.wissiak@ntf.uni-lj.si

Alex Johnstone University of Glasgow, Glasgow, Scotland, UK, alexjo@btinternet.com

Rosária Justi Federal University of Minas Gerais, Brazil, rjusti@uai.com.br

Marijn R. Meijer Universiteit Utrecht, Utrecht, The Netherlands, m.r.meijer@phys.uu.nl

Mauro Mocerino Curtin University of Technology, Perth, WA 6845, Australia, m.mocerino@curtin.edu.au

Ilka Parchmann University of Oldenburg, Oldenburg, Germany, Ilka.parchmann@uni-oldenburg.de

Albert Pilot Universiteit Utrecht, Utrecht, The Netherlands, Pilot1@uu.nl

Irena Sajovic University of Ljubljana, Ljubljana, Slovenia, Irena.sajovic@ntf.uni-lj.si

Vesna Ferk Savec University of Ljubljana, Ljubljana, Slovenia, Vesna.ferk@guest.arnes.si

Lars Scheffel University of Oldenburg, Oldenburg, Germany, Lars.scheffel@uni-oldenburg.de

Keith S. Taber University of Cambridge, Cambridge MA, UK, kst24@cam.ac.uk

Kim Chwee Daniel Tan Nanyang Technological University, Nanyang Avenue, Singapore, daniel.tan@nie.edu.sg

David F. Treagust Curtin University of Technology, Perth, WA 6845, Australia, d.f.treagust@curtin.edu.au

Georgios Tsaparlis University of Ioannina, Ioannina, Greece, gtseper@cc.uoi.gr

Berry Van Berkel Universiteit Utrecht, Utrecht, The Netherlands, b.v.berkel@jea.nl

Hsin-Kai Wu National Taiwan Normal University, Taiwan, Republic of China, hkwu@ntnu.edu.tw

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

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,* Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_1,

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.

Acknowledgments We are grateful to A.L. Chandrasegaran, Keith Taber, Georgios Tsaparlis, and especially to Albert Pilot and Astrid Bulte, for comments on an earlier version of this Introduction.

References

Andersson, B. (1986). Pupils' explanations of some aspects of chemical reactions. *Science Education, 70*, 549–563.

Atkins, P. W. (2005). *Skeletal chemistry*, from http://www.rsc.org/Education/EiC/issues/2005_Jan/skelatal.asp

Ben-Zvi, R., Eylon, B.-S., & Silberstein, J. (1987). Students' visualization of some chemical reactions. *Education in Chemistry, 24*, 117–120.

Bodner, G. M. (1992). Refocusing the general chemistry curriculum. *Journal of Chemical Education, 69*, 186–190.

DeBoer, G. E. (2000). Scientific literacy: Another look at its historical and contemporary meanings and its relationship to science education reform. *Journal of Research in Science Teaching, 37*(6), 582–601.

Fensham, P. J. (1994). Beginning to teach chemistry. In P. J. Fensham, R. F. Gunstone & R. T. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 14–28). London: Falmer.

Gabel, D. L. (Ed.). (1994). *Handbook of research on science teaching and learning*. New York: MacMillan.

Gabel, D. L. (1998). The complexity of chemistry and its implications for teaching. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (Vol. 1, pp. 223–248). London: Kluwer.

Gabel, D. L., Samuel, K. V., & Hunn, D. (1987). Understanding the particulate nature of matter. *Journal of Chemical Education, 64*(8), 695–697.

Gilbert, J. K., Boulter, C. J., & Elmer, R. (2000). Positioning models in science education and in design and technology education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 3–18). Dordrecht: Kluwer.

Harrison, A. G., & Treagust, D. F. (2002). The particulate nature of matter: Challenges to understanding the submicroscopic world. In J. Gilbert, K., O. de Jong, R. Justi, D. F. Treagust & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 189–212). Dordrecht: Kluwer.

Hodson, D. (1990). A critical look at practical work in school science. *School Science Review, 71*(256), 33–40.

Johnstone, A. H. (1982). Macro- and micro-chemistry. *School Science Review, 64*, 377–379.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning, 7*, 75–83.

Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to a changing demand. *Journal of Chemical Education, 70*(9), 701–705.

Johnstone, A. H. (2000). Teaching of chemistry: Logical or psychological? *Chemical Education: Research and Practice in Europe, 1*(1), 9–15.

Laugksch, R. C. (2000). Scientific literacy: A conceptual overview. *Science Education, 84*(1), 71–94.

Marais, P., & Jordaan, F. (2000). Are we taking symbolic language for granted? *Journal of Chemical Education, 77*(10), 1355–1357.

Nakhleh, M. B., & Krajcik, J. S. (1994). Influence of levels of information as presented by different technologies on students' understanding of acid, base, and pH concepts. *Journal of Research in Science Teaching, 31*(10), 1077–1096.

Nelson, P. (2002). Teaching chemistry progressively: From substances, to atoms and molecules, to electrons and nuclei. *Chemistry Education: Research and Practice, 3*, 215–228.

Roberts, D. A. (2007). Scientific literacy/science literacy. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research in science education* (pp. 729–780). Mahwah: Erlbaum.

Shwartz, Y., Ben-Zvi, R., & Hofstein, A. (2005). The importance of involving high-school chemistry teachers in the process of defining the operational meaning of 'chemical literacy'. *International Journal of Science Education, 27*(3), 323–344.

Shwartz, Y., Ben-Zvi, R., & Hofstein, A. (2006). The use of scientific literacy taxonomy for assessing the development of chemical literacy among high-school students. *Chemical Education Research and Practice, 7*(4), 203–225.

Treagust, D. F., Chittleborough, G., & Mamiala, T. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education, 25*(11), 1353–1368.

Tuckey, H., & Selvaratnam, M. (1993). Studies involving three-dimensional visualisation skills in chemistry. *Studies in Science Education, 21*, 99–121.

Part I
The Challenges Faced in Teaching and Learning About the Representational Triplet

This section focuses on the more overt challenges that the teaching and learning of the representational triplet face: the nature and meaning of ‘macro’ ‘submicro’ and ‘symbolic’ and the relationships between them.

In Chapter 1, Bucat and Mocerino address the distinctions between the macro and submicro, focusing on the latter, and the implications that these have for representation. The core of these distinctions lies in the fact that the submicro can only be accessed via imagination. This means that great precision in language is needed if communication, say between teacher (or textbook) and student, about the submicro is to be effective. They point out examples of the many researched cases in which this criterion is not met, leading to the creation of misconceptions in the minds of students. The problems of language are compounded by the need for a range of visual representations to depict all aspects of a given model and by the lack of specific teaching about the interpretative conventions attached to each mode and sub-mode of representation. One type of problem to arise from issues of imprecise language and the need for multiple images is that students fail to see the scope and limitations, as well as the relations between the macro and representations at both the intra-molecular (i.e. those concerned with what happens within molecules) and the extra-molecular (i.e. those concerned with the relationships between molecules) submicro. Switching perception between the macro and the intra-molecular and the extra-molecular submicro requires the exercise of visualization and is found difficult by many students.

In Chapter 2, Van Berkel, Pilot and Bulte take a very different approach to the problems of teaching and learning the macro/submicro relationship. They start by pointing out that much teaching usually involves an introduction to the submicro and proceeds to a consideration of a stylised version of the macro. This counter-experiential approach leaves the student confused: what is being learned and why? Two conventional routes to curriculum development are taken in order to address the inevitable loss of interest and motivation by students. One is to firmly link the submicro to the actual every-day macro experience of students. This fails because that route is often not followed to its logical conclusion: the macro depicted is not recognisable by the students. The second is to add contemporary chemical facts to the curriculum in order to make it relevant and interesting. The outcome is the ‘sedimentary curriculum’ in which content load is progressively and incoherently increased. The authors tie together three schemes of analysis – Robert’s notion of ‘curriculum emphasis’, Schwab’s ‘theory of curriculum substructure’ and Kuhn’s idea of ‘normal chemical education’ – both to describe the nature of the curriculum and to outline an approach to the design of context-based courses that will be intellectually and socially acceptable to students. In doing so, they offer a rationale for the emergence of a more justified and more easily learnt relationship between the macro and the sub-micro.

In Chapter 3, Cheng and Gilbert point to the types of research that are needed if a radical approach, such as that advocated by Von Berkel, Pilot and Bulte, is to be successful. They focus on the submicro level, pointing out the wide range of visual representations that are made use of at the submicro level. These include the many varieties of pictures, diagrams and graphs that are in use. Each of these provides a difference affordance of meaning: where complementary they assist understanding, but where they are contradictory they sow confusion. For a student to have mastery of the submicro, the nature of each mode and submode must be understood, the ways that ‘translate’ between them can be effected must be appreciated, and the capability to construct a desired submicro representation must be present. The ways in which these skills can be appraised are evaluated, a process which will lead to the development of more effective ways of teaching them.

If teaching and learning about the submicro is complex, then that about the symbolic is even more so. In Chapter 4, Taber unpicks in detail the ranges of symbolisms used in chemistry: the spread of types invoked, those used to represent chemical entities and those used to represent reactions between them. In each case, he analyses the educational problems that they present. He concludes with some broad precepts about how symbolic representations might best be presented in chemical education.

Chapter 1
Learning at the Sub-micro Level: Structural Representations

Bob Bucat and Mauro Mocerino

Abstract This chapter examines the importance of visualisation and language, both verbal and pictorial, on the understanding of the sub-microscopic level of chemistry. We begin by examining what is meant by the term ‘sub-microscopic level’ and how it is different from the macroscopic level. Here we stress the need for the careful use of language to distinguish the two levels and we provide some examples of how the imprecise use of language can blur this distinction. The challenges associated with the description and depictions of the arrangement of electrons in atoms, ions and molecules are then addressed. For a good understanding of chemistry it is critical that students visualise chemical reactions as multiple particle processes and examples are provided where misconceptions arise from a single particle perspective. The need for students to learn, and instructors/textbooks to explain, the conventions and styles of molecular representations is then highlighted. Without a good understanding of the meaning of these forms of molecular representations, students cannot visualise spatial/structural features of a molecule or consider implications of these features on reactivity. Finally we return to the need for a clear distinction between the sub-microscopic ‘reality’ and their representations.

What Is the Sub-microscopic Level?

Bent (1984) had a very sharp appreciation of the distinction, and of the interdependent relationship, between the macroscopic and sub-microscopic levels of operation of chemists. He says

> Evidently there’s more to seeing than meets the eye. To see what a chemist sees one needs to know what a chemist knows.
>
> One of my favorite examples of the connection between chemical thought and chemical behaviour is the classic demonstration of the properties of molten sulfur seen through the spectacles of a chemical model.

B. Bucat (✉)
University of Western Australia, Crawley, WA 6009, Australia
e-mail: bucat@chem.uwa.edu.au

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_2,

Bent discusses how the sulphur melts to form a fluid liquid, which then becomes quite viscous before being poured into cold water; we imagine the breaking of S_8 rings, polymerisation of small chains and then ‘quenching’ of the polymeric chains without re-formation of S_8 rings for some time.

> ‘Seeing as a chemist sees is a fact-supported, theory-laden exercise of a lively imagination. The entire covalent chemistry of the non-metals .... is revealed to the mind’s eye in the sulfur-in-a-test-tube-heated-in-air-and-water-quenched demonstration when viewed through the thought-focusing fields of molecular models. To see in that way is to understand. And when we understand in that way, we say ‘I see.’

To elucidate the distinction between the sub-microscopic and macroscopic worlds, Table 1.1 lists some observable chemical phenomena (the macroscopic level) along with the corresponding explanatory models that we use at the sub-microscropic level.

The chemists’ sub-microscopic level concerns the world of atoms and their derivatives; ions and molecules. This is an unobservable world, accessible only by imagination. Imagination is such a key component of advances in chemistry at the research level, as well as of rich student understandings that its significance cannot be underestimated, and we would do well to raise our students’ consciousness of it in order that they might try to develop their visualisation abilities.

Our very first recommendation concerns careful use of language to distinguish between these two levels. Scientists, instructors and textbook writers are all guilty of loose use of language on occasions – with the result that the distinction between the macroscopic and sub-microscopic levels is blurred, rather than sharpened. To be precise, benzene does not have a plane of symmetry (although its molecules do), water is not composed of the elements (as substances) hydrogen and oxygen, C_8H_{18} is not octane (although octane’s composition can be represented as C_8H_{18}), nylon is not a long molecule (although its molecules are long), polyethylene is not an

Table 1.1 Examples of macroscopic and corresponding sub-microscopic levels of chemical operation

Macroscopic behaviour	Sub-microscopic explanation
Pressure of a gas	Collisions of rapidly moving particles on vessel walls
Melting	Temperature is high enough that the particles have enough energy to overcome some intermolecular forces
Sodium chloride dissolves in water	Ion-dipole forces of attraction between water molecules and ions are sufficient to overcome the forces between oppositely charged ions in the solid lattice.
Reactions proceed more quickly at higher temperature	A higher fraction of collisions have total energy of colliding particles greater than the activation energy required for reaction.
A substance displays optical activity	Molecules of the substance are asymmetrical. Interactions between the molecules and electromagnetic radiation is such that the plane of polarisation of the radiation is always rotated in the same direction

enormous alkane, liquid limonene is not chiral (although it is optically active), a reaction energy profile diagram does not plot the energies of the reactants and products during reaction (although it may plot the combined energies of a small group of atoms before, during and after a single fruitful collisional event between reactant molecules, ions or atoms), and the substance concentrated sulphuric acid is a powerful oxidising agent (not the S atom in the +6 oxidation state). That members of the chemistry community know precisely what they mean by such loose statements does not mitigate the lack of awareness of students about the distinction between chemistry's levels. Should we take the trouble to be more careful and precise, even if to do so means being more wordy?

Any discussion of the problematic issues of chemical education will include concerns about how to model for students (and for ourselves!) this 'reality' of atoms, ions and molecules. We should firstly appreciate that there is a tension between the pragmatism of accepting this 'reality', which we try to model, and the truth that this 'reality' is itself a grand model. Perhaps, then, our task is to develop useful students' models of the chemists' models.

We all accept that matter is particulate, and indeed very young pupils are told, and expected to accept, that matter consists of atoms. This is no mean feat: after all many of the best brains in the world, from the times of the ancient Greeks up till the second half of the nineteenth century, debated heatedly whether matter was continuous or particulate. For half a century after Dalton's laws based on an atomic view of matter, this debate raged. Legend has it that Boltzmann's suicide in a fit of depression was brought on by the perception that opponents of the atomic model were winning the day. Regardless of the veracity of this claim, we should perhaps question how facile it is for students to accept the atomic view when the shared understanding of scientists, armed with all of the empirical evidence of the times, took so long to evolve.

One college-level textbook Silberberg (2006) reports:

> 'Atoms? Humbug! Rarely does a major new concept receive unanimous acceptance. Despite the atomic theory's impact, several major scientists denied the existence of atoms for another century. In 1877, Adolf Kolbe, an eminent organic chemist, said "[Dalton's atoms are] . . . no more than stupid hallucinations . . .mere table-tapping and supernatural explanations." The influential physicist Ernst Mach believed that scientists should look at facts, not hypothetical entities such as atoms. It was not until 1908 that the famous chemist and outspoken opponent of atomism Wilhelm Ostwald wrote, "I am now convinced [by recent] experimental evidence of the discrete or grained nature of matter, which the atomic hypothesis sought in vain for hundreds and thousands of years."(p.45)

He was referring to the discovery of the electron.

Why do we accept that matter is particulate? Posed to students, this question can be seen to have two possible levels of intent:

(i) Why do you (the student) believe that all matter comprise particles?
(ii) Why is it the shared understanding of the community of chemists that all matter comprise particles? What is the evidence on which this belief is based?

It is our experience that to the first question, the most common student response is something akin to ‘Because my teacher told me so’. One is tempted to say that it is a pity that the scientific belief of so many students is sourced from an authority, rather than from empirical evidence – except that when chemists are asked question (ii), they find it not at all easy to answer. There is, after all, no single defining experiment that conclusively proves the claim, even though it was the phenomenon of Brownian motion that finally seems to have clinched the day for the atomists 150 or so years ago. Of course, from atomic forced microscopy (AFM), we ‘see’ pictures of gold atoms being manipulated one by one – but the output from AFM is itself the result of application of interpretive models.

Despite all of the above questioning of our sub-microscopic reality, the weight of circumstantial evidence is overwhelming. The ability to use high-precision mass spectrometers to determine not only the molar mass, but the elemental composition of compounds, based on deflection of charged particles in a magnetic field, is convincing. So too are the design and NMR validation of the complex structures synthesised in the supramolecular chemistry research laboratory, and the synthesis of drugs designed specifically to ‘trick’ pathogen molecules by matching regions of molecular shape, perhaps including recognition of chirality.

Let us accept a particulate sub-microscopic world. One of the challenges of chemistry education is to deal with a tension that most macroscopic properties are continuously varying, at least so far as our measurements allow, while our modelling at the sub-microscopic level to explain these macroscopic phenomena is based on a discontinuous picture of matter. Mass, volume, shape, electrical conductivity, solution concentration, the change of reaction rate over time, the dependence of reaction rate on temperature, phase changes, optical activity and the dependence of the equilibrium vapour pressure of solutions on solute concentration are all apparently continuously variable. Reconciliation of the continuous nature of these phenomena with the discrete nature of the explanatory model requires some appreciation of the miniscule size of the particles in our sub-microscopic world. Every teacher knows the difficulty of achieving this unambiguously when we are forced to use descriptors such as ‘particle’ or ‘grain’, to which students have already assigned everyday macro-level meanings.

Accepting atoms as our reality for pragmatic reasons does not address the question of what they are, or what they are like. Many textbooks avoid the awkward question of what they are, preferring instead to simply discuss Dalton’s propositions concerning their existence, and how his model can make sense of the Law of Multiple Proportions, for example. This approach at least emphasises the modelling aspect of their existence. At the first introduction of the concept of atoms to students, attempts to link elements and atoms may include statements such as ‘All of the atoms of an element are the same’. This, of course, has a degree of truth insofar as atomic number and electronic configuration are concerned, but is not correct in relation to the possible existence of isotopes. And yet most would agree that it is not possible to introduce the concept of isotope before a discussion of atoms. What a dilemma!

At least this mode of presentation does not introduce the hazards underlying statements such as ‘An atom is the smallest unit of subdivision of an element that still retains the characteristics of that element'. One can't help but wonder if the findings of early 'misconceptions' research has heightened our sensitivities to the dangers of even tangential suggestion that the properties of particles are those of the macroscopic substance. More than two decades ago, Brook, Briggs, and Driver (1984) diagnosed that some students imagined that the particles melt when substances reach their melting points. Similarly, Ben-Zvi, Eylon, and Silberstein (1986) reported students' conceptions of malleable copper atoms and green chlorine molecules. According to Griffiths and Preston (1992) and Lee, Eichinger, Anderson, Berkheimer, and Blakeslee (1993), there is a common belief that as the temperature of a substance is raised, the particles get hotter. These findings point to the challenges of sub-microscopic representation of phenomena that depend (according to chemists' models) on cooperative interactions amongst particles rather than on the characteristics of the particles themselves.

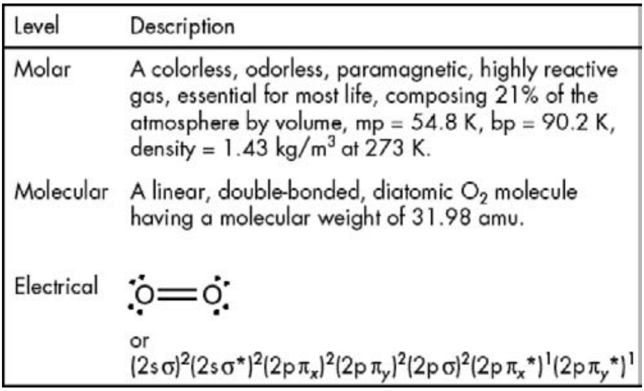
Problems arise from both the limitations of two-dimensional (2D) representations and carelessness in textbook diagrams, and although Hill (1988) referred to such issues long ago, misleading diagrams are still to be seen. Andersson (1990) has brought our attention to a remarkable representation of liquid water showing only 12 water molecules in a beaker of water. That is bad enough, but the same diagram shows these water molecules below a horizontal line representing a liquid surface, suggesting that the water molecules are within a medium, rather than that they actually comprise the medium. An inability to portray a sense of the enormous number of molecules in a beaker of water and of the dynamic nature of even a solid substance is an inherent problem of representation on the printed page. Computers have now opened up new ways of sub-microscopic representation, especially in relation to the dynamic nature of our models.

Fine Resolution: Molecular and Intramolecular Levels

Jensen (1998a) proposes two sub-levels of the imagined sub-microscopic world of atoms: molecules and ions. The *molecular* level concerns structural elements of molecules such as connectivity, bond angles and bond lengths; characteristics that might be 'seen' from nearby molecules. On the other hand, he recognises an *electrical* level, perhaps preferably called the *intramolecular* level, which refers to distribution of electrons within an atom, molecule or ion. In a later paper, Jensen (1998b) makes the distinction between these sub-levels with simple examples in relation to dioxygen gas (Table 1.2).

Visualisation at the intramolecular sub-microscopic level has its challenges. How can we reconcile wave models of electrons in atoms with diagrams that purport to represent probability of position? How difficult to appreciate is the difference between the plot of ψ^2 vs. distance (indicating the probability of finding the electron at a given distance from the nucleus along direction), and the plot of $4\pi r^2\psi^2$ vs. distance (indicating the probability of finding the electron on the surface of a sphere at a given distance from the nucleus)? What is meant by charge density? What challenges are presented in understanding the concept of iso-density contour

Table 1.2 *Aspects of dioxygen gas at the molar, molecular and electrical (intramolecular) levels of discourse*. Taken from Jensen (1998b). (Jensen's use of the term *molar* level corresponds with the more common *macroscopic* level.)



Level	Description
Molar	A colorless, odorless, paramagnetic, highly reactive gas, essential for most life, composing 21% of the atmosphere by volume, mp = 54.8 K, bp = 90.2 K, density = 1.43 kg/m^3 at 273 K.
Molecular	A linear, double-bonded, diatomic O_2 molecule having a molecular weight of 31.98 amu.
Electrical	or $(2s\sigma)^2(2s\sigma^*)^2(2p\pi_x)^2(2p\pi_y)^2(2p\sigma)^2(2p\pi_x{}^*)^1(2p\pi_y{}^*)^1$

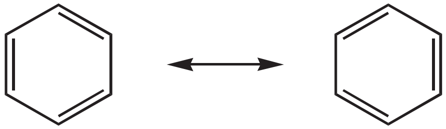
surfaces, of which there are an infinite number? What does it mean that electrons in the 3p orbital of an atom can interpenetrate the distributions of those electrons in the 1s, 2s and 2p orbitals? This latter question begs the further question (theoretically invalid, we believe) of whether electrons in atoms retain their identity. How can one electron in a p orbital have real probabilities of being in either 'lobe', and yet zero probability at a point between the lobes? What is an electron cloud? What does an atom look like?

Keogh (1991) asked high performing first year university students what components they would need to hypothetically construct a lithium atom. One replied that they would need a nucleus, three electrons and an electron cloud. On further investigation, it turned out that this student perceived a need for the electron cloud as a place for the electrons to be put. Despite a 'remedial' discussion, this student demonstrated the same conception several months later.

Representations showing electrons in molecules seem to suggest localisation of the valence electrons, but there are problematic issues in this regard. For example, we might ask if dioxygen has a double bond and two lone pairs on each O atom (as in Table 1.1) – a structure that does not reconcile with the paramagnetic nature of the substance – or a single bond and an odd number of electrons localised on each atom, as shown here:

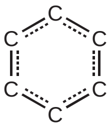
There is not a universally accepted representation of dioxygen's intramolecular electron distribution.

A related issue is that of resonance structures, the classical case of which is benzene. In order to deal with the experimental evidence that all of the C-C bond lengths are equal, it is common to represent the structure of benzene molecules in the following way:

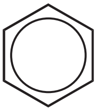


The double-headed arrow is intended to imply the existence of a ‘resonance hybrid’: a structure with an electronic distribution intermediate between the two shown. Every instructor knows the hazards of this portrayal. Firstly, the double-headed arrow is misinterpreted by some students to mean either (i) that there is an equilibrium condition involving the two different species, or (ii) that ‘flipping’ occurs between the two species. A second problem is demonstrated by those students who ask ‘Are these not the same? If we rotate one of the molecules by 60°, we see that they are identical’. We can hypothesise that the latter problem may be exacerbated by the tendency of textbooks (and probably teachers) to talk about these two different resonance structures as though we are referring to two different molecules – when, in fact, we are talking about different electron distributions in just one molecule. It seems so important for instructors to refer to just one set of six carbon atoms joined by σ bonds, and then to discuss alternative distributions of the six π electrons within that system.

Representations less prone to misinterpretation, and perhaps closer to ‘reality’ are the following:

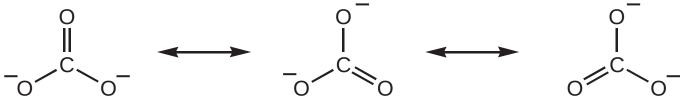


or



These representations are intended to mean that each C–C bond comprises three electrons. This in itself seems not such a difficult concept, but since students are usually ‘indoctrinated’ to the idea that a covalent bond is two shared electrons, the notion of $1^1/_2$ bonds between each pair of C atoms may be bewildering for some.

If this is not difficult enough an idea, have sympathy for students who are told that the carbonate ion, for example, can be represented by the following resonance structures:



One can only wonder what sense some students make of the instruction that the ‘reality’ involves eight electrons distributed over the three C-O bonds: that is, $2^2/_3$ electrons per bond, or each bond equivalent to $1^1/_3$ ‘classical two-electron bonds’!

Professional chemists have a view of a rather fluid, easily distorted, electron cloud in molecules, able to be pushed and pulled by whichever species (or part of a species) is close by. This is an important component of understanding reaction mechanisms, the origin of dispersion forces between non-polar substances, and polarisability of the electron clouds of anions by highly charged cations as explanations of variance of ionic/covalent bond character and acid/base character of metal oxides. While it is common to see textbook discussions of a fluid 'sea of electrons' in metals, there remain challenges for developing, and representing, the idea of fluidity of electron clouds in molecules. In a discussion of the hazards of using curved arrows to denote motions of electrons in representations of reaction mechanisms, Laszlo (2002) makes the following scathing comment about using Lewis formulas in mechanistic representations:

> This limitation was already painfully obvious to the organic chemists in the 1880s: these are static structures, whereas of course any molecule at any temperature is a jelly-like pulsating, librating and vibrating entity. Only a terribly simplistic eye would see a molecule frozen into this Platonic archetype of the structural formula.

Many of the properties of substances are rationalised on the grounds of different electronegativities of bonded atoms, giving rise to polar molecules (unless the symmetry of the molecules causes cancellation of bond dipole moments). The notion that a region of a molecule can have 'partial negative charge' if the amount of electron matter around a nucleus exceeds the charge on the nucleus is a subtle one. Partial charges are usually denoted by δ+ or δ−, no matter on which atoms, in different molecules or within the same molecule. Can we blame students for presuming that the magnitude of charge on the oxygen atom in a water molecule (expressed as δ−) is the same as that on each of the hydrogen atoms (written as δ+)?

An increasingly popular, and very useful, explanatory model of polarity is the electrostatic potential map, an example of which is shown in Fig. 1.1.

In qualitative terms, the more intense the red coloration the greater is the excess of electron charge over nuclear charge, and the intensity of blue coloration indicates the extent to which nuclear charge dominates electron charge in particular regions of the molecule.

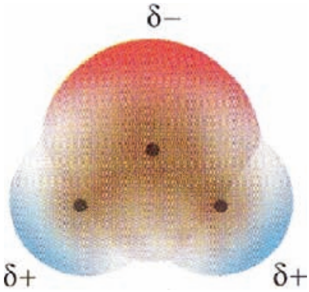


Fig. 1.1 An electrostatic potential map of a water molecule [Scanned from Silberberg (2006, 4th edition)]

While electrostatic potential maps are useful as indicators of likely orientation of molecules to each other, and of points of reactivity to nucleophiles or electrophiles, their precise meaning is not easily accessible to science novices. These maps are achieved by calculation of the potentials of a point unit positive charge at all points on an iso-density surface of the electron cloud, the strength of attraction of the positive charge at some regions being correlated with intensity of red colour, and strength of repulsion at other regions correlated with depth of blue colour.

Students need to be aware that the colours in electrostatic potential maps bear no relationship to portrayal of molecules with differently coloured atoms – such as a red sphere to represent the oxygen atom in a water molecule and white spheres to represent the hydrogen atoms. Of course, while the use of differently coloured spheres to portray different types of atom has some usefulness, it is important that students appreciate the artificiality of the use of these colours. Indeed mature chemical understanding leads to the recognition that atoms do not even retain their identity in molecules. For example, a water molecule does not consist of an oxygen atom and two hydrogen atoms, each of which has ‘its own’ electrons; a more sophisticated view is that it consists of an oxygen nucleus and two hydrogen nuclei surrounded by 10 mutually shared electrons.

Before leaving the subject of distribution of electrons within molecules, and its attribution to the origin of molecular polarity, with consequent effect on intermolecular forces (with further consequent effects on solubilities and melting points), it is pertinent to remind ourselves of two significant challenges faced by chemistry instructors: (i) to graphically represent forces of attraction between molecules and (ii) to develop the imagery that in the liquid state, orientation of molecules toward each other because of polarities is transitory, even if more probable, as they move past each other.

Fine Resolution: Single-Particle and Many-Particle Images

Further resolution of the sub-microscopic world at Jensen’s molecular level can be useful. Bucat (2004) has stressed the importance of recognition that sometimes we use single-particle images, and sometimes it is necessary to use many-particle images. For example, we generally use representations of single molecules to understand (i) connectivity and bond angles, (ii) stereochemistry, (iii) *cis–trans* isomerism and (iv) molecular polarity. On the other hand, it is not possible to rationalise boiling, or dissolving, with a portrayal of just one molecule of a substance – even though a visualisation of a polar molecule, for example, might help us to understand different boiling points or solubilities. Similarly, rationalisation of chemical equilibrium, the states of matter (or changes between them), diffusion, optical activity, or brittleness of ionic solids demand visual images with many particles to make sense.

Does it matter? The following, some taken from research and some from experience, provide justification for employing this fine resolution to analysis of pedagogical issues in chemistry teaching. Ben-Zvi, Eylon, and Silberstein (1987) have shown that some school students in Israel have responded to a question asking whether it is possible for N_2O_5 to be formed by reaction between N_2 and O_2 by saying 'No. Where from did we get three additional oxygen atoms?' Obviously these students did not appreciate that they needed to consider a many-particle picture in this situation. Ben-Zvi et al. speculate that this may be because textbooks usually present single-particle images to portray chemical reactions.

Ladhams Zieba (2004) has found that university students can be confused when a single-particle representation of S_N1 substitution leads to a racemic mixture of products (Fig. 1.2).

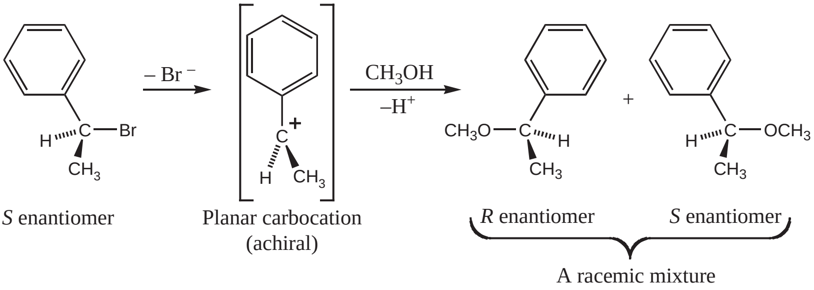


Fig. 1.2 A single particle representation of racemate production

How can we get two molecules of product from only one molecule of starting compound? Perhaps, at least until students are more experienced, this diagram needs to be supplemented by a diagram or animation showing many reactant particles, half of which form one enantiomer and half the other enantiomer.

The accepted mechanism of S_N2 substitution reactions is based on the experimental evidence that their reaction rates are directly proportional to the concentrations of both the substrate and the nucleophile. However, in discussion of this type of reaction, textbooks usually present a single-particle representation of the process (Fig. 1.3).

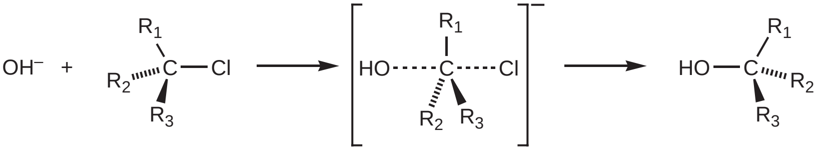


Fig. 1.3 A single-particle representation of an S_N2 substitution reaction

It is common experience that, when given this diagram, many university students say that what is meant by 'the rate of the substitution reaction' is how quickly the single event portrayed in the diagram happens. However, there is no sense to be made from the notion that the speed of this single event depends on the concentrations of both reactants. Of course, the real meaning of ‘rate of reaction’ concerns how many such reaction events occur per unit time, and this meaning can only be developed with a multi-particle image of the reaction mixture.

Visualisation of a chemical reaction as a single event is sometimes unconsciously encouraged by the language that we use. For example, this extract placed alongside a mechanistic representation of an S_N2 substitution reaction from a popular textbook is similar to that in many others:

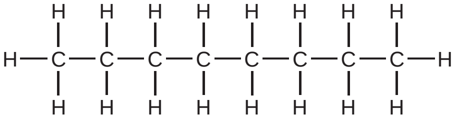
> The nucleophile OH^- uses its lone pair electrons to attack the alkyl halide carbon 180° away from the departing halogen. This leads to a transition state with a partially formed C-O bond and a partially broken C-X bond. The stereochemistry is inverted as the C-O bond fully forms, and the halide ion departs with the electron pair from the former C-X bond.

Only one nucleophile particle and only one alkyl halide molecule? One bond broken and one bond formed? Leaving aside the implication of intent on the part of the nucleophile (rather than a probabilistic view of the event), this extract would be acceptable if it were explicitly stated that it focussed on just one of the very many reaction events that occurred at various points in time in the reaction mixture.

A less obvious example that needs careful consideration to understand is our usual explanation of the dependence of reaction rates on temperature. Two diagrams are usually used in conjunction: (i) the so-called reaction energy profile diagram indicating an activation energy barrier and (ii) a Boltzmann distribution of kinetic energies of the reactant particles. We need to be aware that the former concerns the combined energies of particles in a single-particle (of each reactant species) event, while the latter relates to statistical distribution of energies of the very many particles in the reaction mixture. It is by no means certain that students comfortably and successfully reconcile the vastly different contexts of these two diagrams.

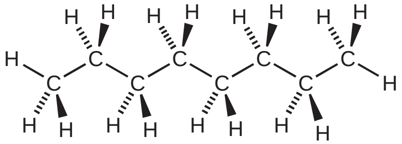
Portrayal of Structures of Molecules

Portrayal of molecules is done in a large variety of ways, each having particular advantages and disadvantages. It has been common for textbooks to present a molecule of octane, for example, in the following form:



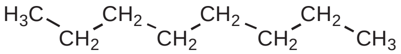
$$\begin{array}{ccccccccccccccccccc} & & H & & H & & H & & H & & H & & H & & H & & H & & \\ & & | & & | & & | & & | & & | & & | & & | & & | & & \\ H & — & C & — & C & — & C & — & C & — & C & — & C & — & C & — & C & — & H \\ & & | & & | & & | & & | & & | & & | & & | & & | & & \\ & & H & & H & & H & & H & & H & & H & & H & & H & & H & & \end{array}$$

This type of representation, probably used because of limitations in typesetting technology in the past, indicates connectivity correctly, but gives a very poor image of the bond angles and the flexibility of the carbon chain due to the rotation about single C-C bonds. A much more powerful image is the following, which at least portrays the tetrahedral arrangement of bonds around each carbon atom.



To ‘read’ this structural representation, one needs to understand the inherent conventions concerning ‘wedge’ and dashed lines. But even this portrayal is static, able to show neither the vibrations of the atoms nor rotation about the single bonds – giving rise to the apparent twisting of the chain into more probable orientations. Furthermore, it is limited in its ability to show the most stable staggered conformer, and does not make obvious the steric hindrances that may arise because of the size of atoms or functional groups (as a space-filling model can). Very powerful computer simulations that seem to have great potential as visualisation aids are now available.

Abbreviated forms of the octane molecular representations include the following:



These last two portrayals demand knowledge of how to ‘read’ them and the last (so-called ‘line structure’) can be tricky for students to interpret, especially in the case of more complex molecules and cyclic structures.

Bodner and Domin (2000) demonstrated the inability of many university students to interpret abbreviated structural portrayals with some atoms implied, rather than shown. The students were asked to predict the major products of the reaction of bromine with methylcyclopentane portrayed as in Fig. 1.2, and to estimate the ratio of the products if bromine radicals were just as likely to attack one hydrogen atom as another. Most of the 200 students predicted three products, with a relative abundance 3:2:2 (Fig. 1.4).

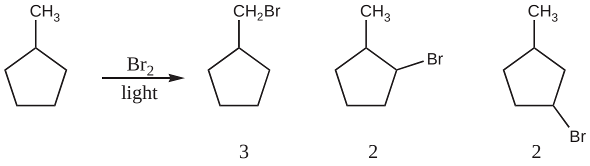


Fig. 1.4 Products, and relative abundances, predicted by most students in the research of Bodner and Domin

A minority of students correctly predicted four products in the ratio 3:4:4:1 (Fig. 1.5).

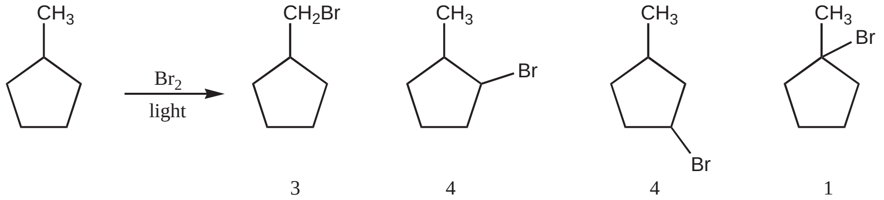


Fig. 1.5 The correct prediction required students to realise that there is a hydrogen atom at the carbon with methyl substituent, and two hydrogens at each other ring carbon

The remarkable finding from this research was that every student who answered correctly firstly re-drew the starting material as shown in Fig. 1.6, and none of those who answered incorrectly did so. The recognition of implied atoms is something that we do automatically as we become more experienced in chemistry.

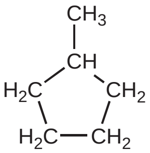


Fig. 1.6 The re-drawn structure of methylcyclopentane, showing all hydrogen atoms, that was the key to students answering correctly the task given by Bodner and Domin (2000)

Chemists do not make things easy for the novice: molecules of a substance can be represented in a variety of ways to illustrate particular features, and to the novice these can seem to be different structures. Hoffman (1995) and Hoffman and Laszlo (1991) illustrate this point well through various representations of a molecule of camphor (Fig. 1.7).

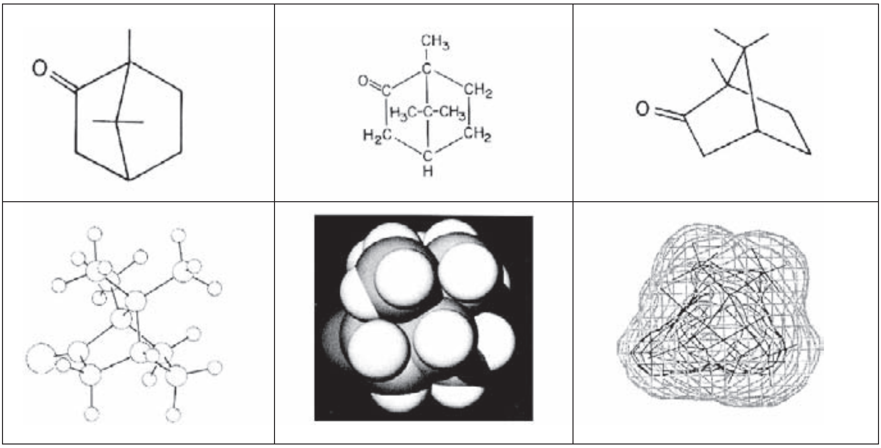


Fig. 1.7 Different-looking representations of a camphor molecule (From Hoffmann and Laszlo, 1991)

Spatial Visualisation: Demands and Abilities

Operation at the sub-microscopic level of chemistry requires a degree of imagination and visualisation ability that differs from person to person. Valuable essays on the importance of these visualisation abilities have been published by Francoeur (1997), Habraken (1996, 2004), Hoffmann (1995), Hoffmann and Laszlo (1991), Briggs and Bodner (2007) and Kozma and Russell (2007).

For example, chemists are required to interpret diagrams of a molecule of cyclohexane, or of substituted cyclohexanes, when it is represented as a flat-looking hexagonal projection, or as a side-on view to show the 'chair' form, or as a Newman projection (Fig. 1.8).

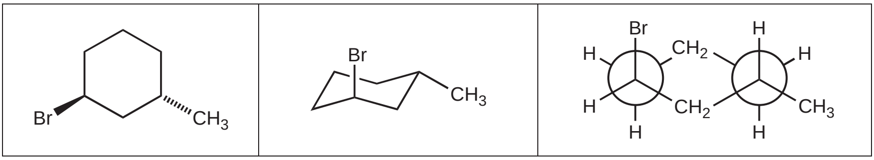


Fig. 1.8 Different representations of 2-bromomethylcyclohexane

Even using the same style, chemists can represent a simple methyl group in different ways, as demonstrated in the example of methylcyclohexane (Fig. 1.9). A chemist will interpret these diagrams, usually subconsciously, as all being equivalent in that they all represent the same molecule, methylcyclohexane.

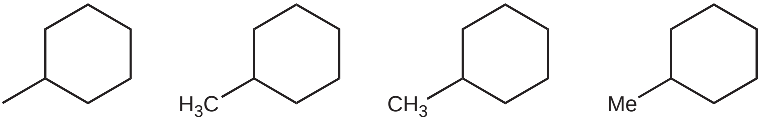


Fig. 1.9 Different representations of a methyl group in methylcyclohexane (From Hoffmann and Laszlo, 1991)

Bodner and Domin (2000) provide research evidence that even some university students do not find it easy to visualise these structures. Students were asked to give the systematic names of the compounds whose molecules were represented as in Fig. 1.10.

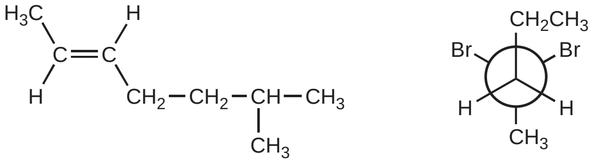


Fig. 1.10 Representations given in the naming exercise given by Bodner and Domin (2000)

Although most students were successful with the structure on the left, many could not name the one on the right, even in two later exams during the same course. The students complained that this question was ‘not fair’, apparently because they had trouble in visualising a side view of the molecule. This finding is consistent with earlier work that demonstrated the difficulty that many students find with tasks that involve (i) interpreting a 2D representation into a 3D image, (ii) performing a mental operation, such as rotation or reflection, on the 3D image and (iii) re-representation of the newly visualised 3D image as a 2D diagram (Seddon, Tariq, & Dos Santos Viega, 1982, Seddon & Shubbar, 1984, Tuckey, Selvaratnam, & Bradley, 1991). Head, Bucat, Mocerino, and Treagust (2005) report similar findings with respect to changing one’s mind’s-eye perspective from one style of representation of a molecule of a substituted cyclohexane to another style of representation. Both Ferk, Blejec, and Gril (2003) and Kuo, Jones, Pulos, and Hyslop (2004) have demonstrated better student understanding with physical models than with schematic representations.

In the case of representation of chiral molecules, the demands of spatial visualisation ability on understanding become critical. Head and Bucat (2002) have reported the outcomes from interviews with students and lecturers in relation to tasks such as that shown in Fig. 1.11.

Fig. 1.11 A task used by Head and Bucat (2002) to probe visualisation abilities

Alanine: Are these mirror images or superimposable?

They report wide differences of visualisation abilities (of both students and lecturers) and that each person consistently employed idiosyncratic decision-making strategies from task to task. Most students employ a strategy of rotation to align a corresponding bond in each structure, thus reducing the problem to a 2D consideration of the clockwise/anticlockwise orientation of the other three function groups. The students found mental rotation about the vertical bond easier than about the other bonds. This is consistent with the findings of Kuo et al. (2004) who investigated student’s strategies of assigning R or S configurations to structures of chiral molecules. Students found the task easier when the lowest-priority group was oriented towards the back or the side of the molecular representation, rather than towards the top or to the front.

Distinguishing Between Representations and the Reality Represented

Common teaching experience suggests that sometimes students’ sense-making operates on representations, rather than on the sub-microscopic ‘reality’ that they represent. How powerful it would be if, on seeing a formula, a molecular structure, a diagram of molecular interaction, or a chemical equation, students visualised the substance or the reaction mixture, rather than the symbolism on the page or computer screen. There is research evidence that this is, at least sometimes, not the case.

Kleinman, Griffin, and Kerner (1987) refer to a student who was shown a diagram of bromobenzene (Fig. 1.12) and asked if the molecule has a plane of symmetry.

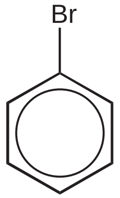


Fig. 1.12 A diagram of a bromobenzene molecule, similar to that used by Kleinman et al. (1987)

The student decided that the molecule does not have a plane of symmetry because, referring to the bromine atom, B $\neq$ r.

Ladhams-Zieba (2004) has demonstrated that university students working on reaction mechanisms in organic chemistry also operate on the drawings on the page, rather than on what they represent. She asked 18 second year university students to predict and draw the product species most likely to be produced from the substitution reaction of hydroxide ion into 2 bromobutane, represented as in Fig. 1.13(a). Ten of them drew the inverted substitution product that you might expect from 'backside attack' in an S_N2 reaction (Fig. 1.13(b)).

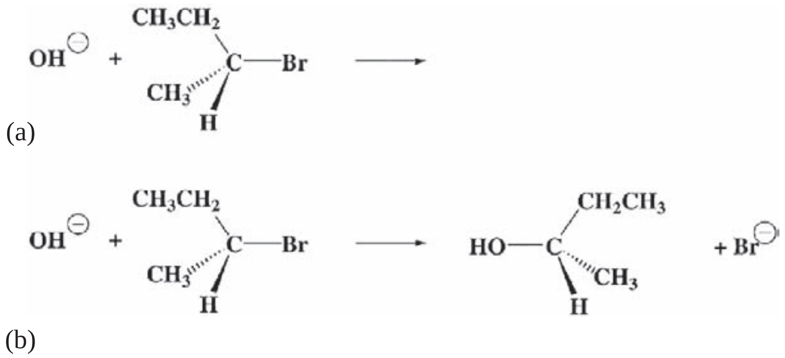


Fig. 1.13 (**a**) shows the task presented to students and (**b**) shows the dominant answer

By contrast, 17 other students were given the same task, except that they were given an equation in which the positions of the formulas of the two reactant species are reversed (Fig. 1.14(a)). Eight of the students drew a substitution product with-

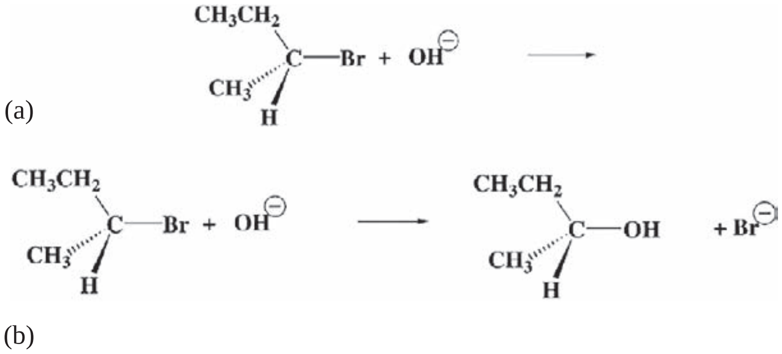


Fig. 1.14 The former shows the task presented to students and the latter shows the dominant answer

out inversion, as though the hydroxide and bromide had simply changed places (Fig. 1.14(b)) and only one of the others predicted inversion.

The predicted product shown in Fig. 1.14 is different from that shown in Fig. 1.13, even though the reactants are the same. Of course it is nonsense to think that the product of a reaction between two species could depend upon the relative positions of their formulas in a representation of a reaction equation. This is clear evidence that some students consider the juxtaposition of the written representations of the reactants on the page, rather than a visualisation of the reaction mixture at the sub-microscopic level. The quality of the predictions would have been greatly enhanced if the students had visualised a many-particle, probabilistic picture of the reaction mixture, as discussed earlier

Conclusion

On its own, the imagined world of sub-microscopic chemistry presents serious challenges for students and, therefore, for teachers. Not the least challenge is that it is indeed an imagined world. Given that this sub-microscopic world must be knitted into the kindred worlds of observable macroscopic behaviour and symbolic representations, the complexity of learning chemistry is revealed. There is a need for clear understanding of the conventions and styles of molecular representations and therefore the teaching of these conventions. Without such an understanding, students cannot then visualise spatial and structural features of a molecule nor consider implications of these features on reactivity. Perhaps the eventual seamless weaving of the three worlds of chemistry will be made easier for students if initially the distinction between them is explicitly emphasised. Starting from a sharp consciousness of the different worlds can lead to a more comfortable and effective operational mode than can be achieved from a condition of confusion or simply lack of recognition of these levels of chemistry.

References

Andersson B. (1990). Pupils' conceptions of matter and its transformations (age 12–16), *Studies in Science Education, 18*, 53–85.

Bent, H. A. (1984). Uses (and abuses) of models in teaching chemistry. *Journal of Chemical Education, 61*(9), 774–777.

Ben-Zvi, R., Eylon, B.-S., & Silberstein, J (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*(1), 64–66.

Ben-Zvi, R., Eylon, B.-S., & Silberstein, J. (1987). Students' visualisation of a chemical reaction. *Education in Chemistry, 24*(4), 117–120, 109.

Bodner, G., & Domin, D. S. (2000). Mental models: The role of representations in problem solving in chemistry. *University Chemistry Education, 4*(1), 22–28.

Briggs, M., & Bodner, G. (2007). A model of molecular visualization. In Gilbert, J. K. (Ed.), *Visualization in science education*. Dordrecht: Springer.

Brook, A., Briggs, H., & Driver, R. (1984). *Aspects of secondary students' understanding of the particulate theory of matter*. Leeds: Centre for Studies in Science and Mathematics Education, University of Leeds.

Bucat, R. (2004). Pedagogical content knowledge as a way forward. *Chemistry Education: Research and Practice, 5*(3), 215–228.

Ferk, V., Blejec, A., & Gril, A. (2003). Students' understanding of molecular structure representations. *International Journal of Science Education, 25*(10), 1227–1245.

Francoeur, E. (1997). The forgotten tool: The design and use of molecular models. *Social Studies of Science, 27*(1), 7–40.

Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*(6), 611–628.

Habraken, C. L. (1996). Perceptions of chemistry: Why is the common perception of chemistry, the most visual of sciences, so distorted? *Journal of Science Education and Technology, 5*(3), 193–201.

Habraken, C. (2004). Integrating into chemistry teaching today's student's visuospatial talents and skills, and the teaching of today's chemistry's graphical language. *Journal of Science Education and Technology, 13*(1), 89–94.

Head, J., & Bucat, B. (2002). Visualisation and mental manipulation of molecular structures. *Australian Journal of Education in Chemistry, 59*, 25–29.

Head, J., Bucat, R. Mocerino, M., & Treagust, D. (2005). Exploring students' abilities to use two different styles of structural representation in organic chemistry. *Canadian Journal of Science, Mathematics and Technology Education, 5*(1), 133–152.

Hill, D. (1988). Misleading illustrations. *Research in Science Education, 18*, 290–297.

Hoffman, R. (1995). *The same and not the same*. Columbia University Press, New York.

Hoffmann, R., & Laszlo, P. (1991) Representation in chemistry. *Angewandte Chemie - International Edition in English, 30*(1), 1–16.

Jensen, W. B. (1998a). Logic, history and the chemistry textbook: I. Does chemistry have a logical structure? *Journal of Chemical Education, 75*(6), 679–687.

Jensen, W. B. (1998b). Logic, history and the chemistry textbook: II. Can we unmuddle the chemistry textbook? *Journal of Chemical Education, 75*(7), 817–828.

Keogh, L. A. (1991). *Student conceptions of atomic matter: A phenomenographic study*. Unpublished Honours thesis, Department of Chemistry, The University of Western Australia.

Kleinman, R. W., Griffin, H. C., & Kerner, N. K. (1987). Images in chemistry. *Journal of Chemical Education, 64*(9), 766–770.

Kozma, R., & Russell, J. (2007). Students becoming chemists: Developing representational competence. In Gilbert, J. K. (Ed), *Visualization in science education*. Dordrecht: Springer.

Kuo, M.-T., Jones, L. L., Pulos, S. M., & Hyslop, R. M. (2004). The relationship of molecular representations, complexity, and orientation to the difficulty of stereochemistry problems. *The Chemical Educator, 9*(X), 1–7.

Ladhams Zieba, M. (2004). *Teaching and learning about reaction mechanisms in organic chemistry*. PhD thesis, University of Western Australia, http://theses.library.uwa.edu.au/adt-WU2005.0035/ (accessed October 2007).

Laszlo, P. (2002). Describing reactivity with structural formulas, or when push comes to shove. *Chemistry Education: Research and Practice in Europe, 3*(2), 113–118.

Lee, O. Eichinger, D. C., Anderson, C. W., Berkheimer, G. D., & Blakeslee, T. D. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*(3), 249–270.

Seddon, G. M., Tariq, R. H., & Dos Santos Viega, A. (1982). The visualisation of spatial transformations in diagrams of molecular structures. *European Journal of Science Education, 4*, 409–420.

Seddon, G. M., & Shubbar, K. E. (1984). The effects of presentation mode and colour in teaching visualization of rotation in diagrams of molecular structures. *Research in Science and Technological Education, 2*(2), 167–176.

Silberberg, M. S. (2006). *Chemistry: The molecular nature of matter and change* (4th ed.). New York: McGraw-Hill.

Tuckey, H., Selvaratnam, M., & Bradley, J. (1991). Identification and rectification of student difficulties concerning three-dimensional structures, rotation and reflection. *Journal of Chemical Education, 68*, 460–464.

Chapter 2
Micro–Macro Thinking in Chemical Education: Why and How to Escape

Berry van Berkel, Albert Pilot and Astrid M. W. Bulte

Abstract Although the learning of micro–macro thinking is a key conceptual area in chemistry, it is perceived as difficult and abstract. Two strategies have been applied to address this problem: the use of contexts and a regular update with contemporary content. In this chapter, we describe how curriculum development can fall back into a typical dominant version of school chemistry, especially for the area of micro–macro thinking. This 'fall back' can be explained by a synthesis of curriculum theories based on the ideas of curriculum emphases (Roberts), curriculum structures (Schwab), normal science (Kuhn) and curriculum representations (Goodlad). This theory describes the dominant version of school chemistry as a curriculum with a typical philosophical substructure of educational positivism, a substantive substructure based on corpuscular theory and a pedagogical substructure focusing on the initiatory and preparatory training of future chemists. For an escape from these constraints, a *co-ordinated replacement* of the currently rigid combination of substantive, philosophical and pedagogical substructures of school chemistry will be necessary. A successful curriculum development implies the consistent transformations between curriculum representations: from a vision on chemistry education into design criteria for an entire curriculum (1), into an exemplary unit (2), into student and teacher materials (3), into the operational form in a real classroom, with attained learning results of students (4). Evaluative feedback loops of the transformations support the iteration in the development. In Chapter 9 of this book a first step towards such a unit is described.

What Is the Problem with Macro–Micro Thinking in School Chemistry?

> 'Most of us who are scientists have enjoyed climbing this ladder as part of our education. We revel in the lofty view from the top. 'Unfortunately, many students do not see the connection between the successive rungs. They are not told and do not discover why or

---

B. van Berkel (✉)
Universiteit Utrecht, Utrecht, The Netherlands
e-mail: b.v.berkel@jea.nl

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,* Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_3,

> where they are climbing. Before long they develop vertigo. Often they jump or fall off the ladder before they reach the top. All they take from the experience is distaste for science'. (Schwartz, 2006)

Figure 2.1 is presented as a metaphor for the problems students have when trying to learn about micro–macro thinking. The philosophy of mainstream chemistry curricula is that students need to climb a ladder: the understanding of interesting real-life phenomena can only be reached when a student understands the corpuscular 'building blocks' of chemistry, the atoms and molecules. However, it takes a 'long climb' for students to come to a point where interesting, relevant themes are dealt with; it requires more time than is available within the limits of the school chemistry curriculum. Long before most students will have developed vertigo. The result is that learning micro–macro thinking is abstract and thus difficult for students; all they go away with is a perception that learning chemistry is meaningless. They have most likely acquired a bad taste for chemistry.

Numerous examples of 'climbing the ladder' can be found in textbooks for secondary education. For example, textbooks start the study of the subject of 'salts' with the (sub-) microscopic particles of atoms and molecules, followed by how atoms 'theoretically' are converted into ions, and how ionic substances are built from charged ions. Textbooks continue with the macroscopic property of the solubility of ionic substances in water. Subsequently more complex ions, such as sulphates and nitrates, are addressed to become part of the students' repertoire using the sub-microscopic world of chemistry and the symbolic representations. For other subjects, such as organic chemistry, the pathway for study from the basic sub-microscopic particles and related chemical principles to making sense of a relevant macro-world of applications (e.g. production of medicines) is very long. Moreover, the sub-microscopic world of state-of-the-art chemistry has become very complex.

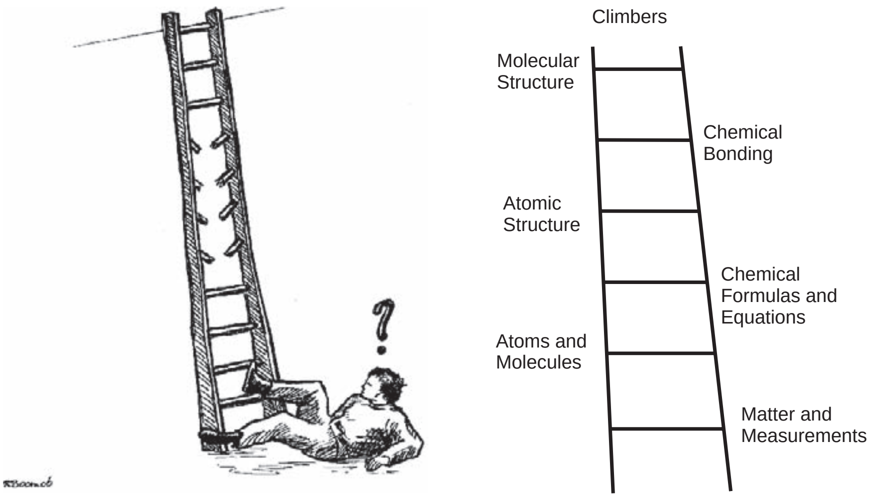


Fig. 2.1 'Climbing the ladder and developing vertigo' as a metaphor for the problematic situation of the domain of micro–macro thinking in chemical education

The separate parts in the school chemistry textbooks are accompanied by student-exercises that mainly aim to train the students' ability to reproduce the chemical knowledge presented. It takes quite a large number of chemistry lessons before a student will come to a point where the new chemical knowledge may be related to society and the everyday world. Only some students start to ask about nitrates and environmental problems while climbing the ladder. Many never make such a connection. According to the common curriculum philosophy that students first need to 'climb the ladder', it takes a 'long climb' for students to see the relevance to societal themes: in fact it is impossible within the (time) limits of the school chemistry curriculum.

Previous Attempts to Solve the Problem of Micro–Macro Thinking

In the past the experienced lack of meaningfulness of learning about atoms and molecules has been addressed by two types of strategy. The first strategy has been to try to connect students' learning to their daily-life experiences. The second strategy has been founded on the proposition that the school chemistry curriculum can be kept connected to contemporary chemical and technological developments by a regular update of the content. Both strategies are exemplified below, including the possible result of such strategies when such curriculum development takes place without a careful analysis of the underlying philosophy.

The first strategy is to undertake a superficial scan of mainstream textbooks that everyday situations have been connected to common school chemistry textbooks. For example, student-exercises may contain information, about contaminants in a river such as lead salts, about acid–base indicators in plants or about food additives for the preservation of wine. However, implicit confusion may (and frequently will) occur when the textbook and the teacher aim at reaching the 'right' answer, for example the correct calculation of the concentration of an additive in gram per litre or parts per million (ppm). Students may still pose questions such as: 'How many glasses of wine can I drink before I will get sick? What is the effect of alcohol on my body? Why is the addition of sulphite to wine important? Is the same fact true for red wine?' Or even further: 'Shouldn't the government prohibit the addition of sulphite?' In this way students can become personally involved in subjects that can be related to their learning of chemical substances, and even to atoms and molecules. But, the student-activities in mainstream school chemistry textbooks often are not focused on this type of involvement; they do not put emphasis in the curriculum on personal, socio-scientific and ethical questions that are relevant to students' lives and society.

Implicit or explicit shifts in purpose can be described in terms of Roberts' concept of 'curriculum emphasis'. An emphasis, according to Roberts, is defined as (1982, p. 245)

> [A] coherent set of messages to the student about science (rather than within science). Such messages constitute objectives which go beyond learning the facts, principles, laws and

> theories of the subject matter itself – objectives which provide an answer to the student question: "Why am I learning this?"

The framework for the concept of curriculum emphasis should be seen as (Roberts, 1988, p. 27)

> [A]n analytical framework for understanding what is involved for policy makers, and for science teachers, when they shape answers to the question: What counts as science education?

Based on an historical analysis, Roberts distinguished seven types of emphases for science curricula, for example *Solid Foundation* that focuses on science as cumulative knowledge, *Science, Technology and Decisions* that focuses on the role scientific knowledge plays in decisions which are socially relevant, *Structure of Science* that focuses on the 'conceptual system for explaining naturally occurring objects and events, which is cumulative and self-correcting' through a process of enquiry and *Personal Explanation* that focuses on one's own way of explaining events in terms of personal and cultural (including scientific) influences. Roberts stresses the importance to maintain consistency of the message within a unit of a curriculum. One curriculum emphasis in one particular unit should not be mixed up with another emphasis, in order to avoid confusion about what message is to be learned and why it is to be learned.

The example illustrating the first strategy described above shows how confusing messages to students can be when learning about corpuscular theories in chemistry lessons. The teacher and the textbook intend to offer students a *Solid Foundation*, while students may want to address questions within a *Science, Technology and Decisions* emphasis. The situation could also be the other way around: a textbook or a teacher aiming to address socio-scientific issues, ethical and personal questions (*Science, Technology and Decisions*), while students think they have to come up with the correct answers (in a *Solid Foundation* emphasis; cf. Hoffmann & Coppola, 1996). A mixing of emphases leads to confusing messages in chemistry lessons about what should be learned and why, for example, the learning about molecules and atoms is relevant (cf. Osborne & Collins, 2001; Westbroek, 2005).

In chemical education, the micro-world is a key perspective in viewing the macroscopic world around us. Among other perspectives, such as a personal, a socio-economical perspective, a political perspective, this key chemical perspective can offer students a view on the materials and substances they use, that they are made of and that constitute their material world. A micro-world perspective enables the understanding of many phenomena and offers the possibility to improve the material world within social circumstances.

In order to make the learning of chemistry, including molecules and atoms, more meaningful to students, context-based approaches have been developed since the 1980s (cf. Bennett & Lubben, 2006; Parchmann et al., 2006). These approaches are designed to improve both relevance and conceptual understanding (cf. Bennett & Holman, 2002; Pilot & Bulte, 2006; Bennett, Lubben & Hogarth, 2007). To avoid mixed messages, it is important to have in-depth knowledge of the problematic features within the domain of micro–macro thinking and to understand what it is that is to be communicated to students and how this is best communicated to them. This means that we should avoid mixing curriculum emphasis as has been the case in previous curriculum developments. Making clear and consistent decisions on the curriculum emphasis of units is necessary in order to escape from the existing confusion, and we will discuss this issue in more detail in the section on recommendations.

With respect to the second strategy, the update of chemical content, De Vos and Pilot (2001; see also De Vos, Bulte and Pilot 2002) have described how curriculum redesign over the years has resulted in a sedimentary structure which they detail for the topic of acid and bases. They describe how successive layers of historical developments in the area of chemistry can be identified in the schoolbooks. Within the perspective of this chapter we relate these layers to the domain of micro–macro thinking. Different historical developments have followed over the years: e.g. Lavoisier, ionic and equilibrium theory, Brønsted and Lewis theories, biochemical theories related to environmental issues and to daily life. Such historical developments left marks on the use of the concept of ‘acid’ in textbooks. For example, a typical textbook may start with tasting ‘acids’ (everyday life – macroscopic). A next layer may be ‘acid’ as a solution, e.g. vinegar (a macroscopic phenomenon often explained with sub-microscopic theories). A further layer may be a substance: acetic acid (Lavoisier – macroscopic), or may be a solution of the substance as a certain concentration of acetic acid in water (macroscopic). Subsequently, texts continue by explaining the pH scale by colours of universal indicator (macroscopic). And often in the next sections the ‘acid’ has become a particle (ionic and equilibrium theory – sub-microscopic) from which a proton can be removed (Brønsted – sub-microscopic). The inconsistent use of a label such as ‘acid’ makes coherence within a textbook chapter problematic. De Vos and Pilot (2001) show that these layers of strata are not a result of a well thought out pedagogical strategy. Instead, it is an unintended product of a historical process: an accumulation of successive, separated and implicit decisions leading to an incoherent patchwork of acid–base theories, very difficult to learn and to teach, and with inconsistencies between the sedimentary layers.

This example of the second strategy shows how historical layers remain present within a curriculum. As De Vos and Pilot (2001) have argued, there is a strong tendency over the years to survey the chemical content that becomes available. Content retention has led to a curriculum paradox: while historical layers remain, the addition of content as a result of the survey means that the curriculum has become overloaded with content. Also, it becomes more and more resistant to the accommodation of new developments with an increased risk of isolation from social, everyday, contexts, while a learner may be interested in understanding and modifying materials and their properties. More adaptation is needed than just adding the latest scientific and technological developments in genetic engineering, biochemistry and nanotechnology. A thorough redesign is needed, in which micro–macro thinking is a key concept.

Therefore, it is important to consider strategies which take the results of a thorough analysis of current micro–macro teaching and learning into account and to produce instruments for the development of new curricula, since both these strategies are among recent curriculum innovations (cf. ‘Chemie im Kontext’ in Germany:

Parchmann et al., 2006; ‘Nieuwe Scheikunde’ in the Netherlands: Driessen & Meinema, 2003). For this purpose, we use a synthesis of frameworks and combine this into a domain-specific curriculum theory (Van Berkel, 2005). Van Berkel’s theory is based on the work of Roberts on curriculum emphases, of Schwab on curriculum structures, of Kuhn on normal science and scientific training and that of Goodlad et al. on curriculum representations.

How Can Chemistry Curricula Be Described?

It is important to understand both how to avoid implicit shifts of emphases and how to avoid incoherent historical layers of content in chemistry curricula. Both strategies, to connect to daily-life experience and to update content, call for a careful analysis with respect to the content of the school chemistry in the domain of micro–macro thinking. What constitutes a meaningful chemistry curriculum in relation to the domain of micro–macro thinking needs a thorough understanding, especially at a time when there is an urge to implement both everyday contexts and new contemporary science and technology. A proper diagnosis is necessary for effective treatment of the problem in order to achieve meaningful learning of micro–macro thinking. We therefore use a synthesis of theories and frameworks and combine this into a domain-specific curriculum theory (Van Berkel, 2005).

According to Schwab (1964a, 1978), a curriculum can be interpreted theoretically in terms of three substructures: the substantive (*Sub*), the philosophical (*Phil*) and the pedagogical (*Ped*), which should together form a coherent set that fit together (cf. the fitting jig-saw puzzle in Fig. 2.2).

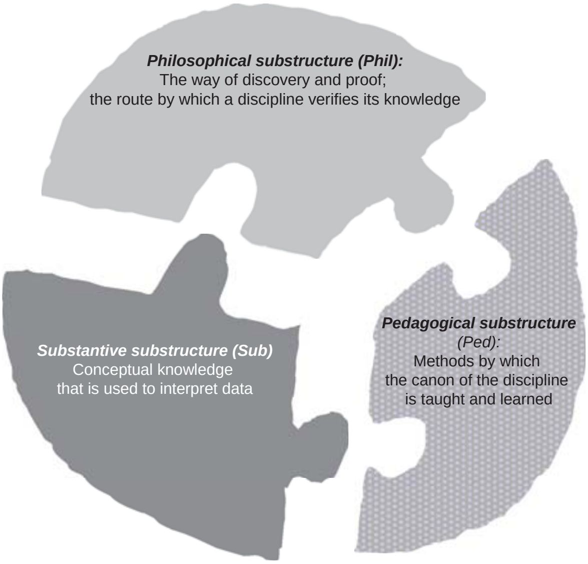
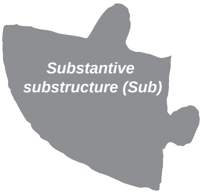


Fig. 2.2 The substructures of a curriculum according to Schwab (1964a, 1978)

Substantive Substructures of the Disciplines

Schwab (1964a, p. 12) gives the following description of the function of a substantive substructure of a discipline, or conceptual substructure as he alternatively calls it:

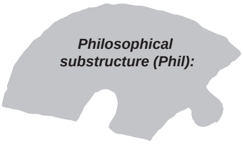


> ‘In general, then, enquiry has its origin in a conceptual structure, often mathematical, but not necessarily so. It is this conceptual structure through which we are able to formulate a telling question. It is through the telling question that we know what data to seek and what experiment to perform to get those data. Once the data are in hand, the same conceptual structure tells us how to interpret them, what to make of them by way of knowledge. Finally the knowledge is formulated in the terms provided by the same conception’.

Schwab mentions three important characteristics which the substantive substructures of the natural science disciplines acquired more and more in the twentieth century. First, the substantive substructures of a discipline are not one, but many. Schwab, himself a biologist, gives some specific examples from the science of biology such as the taxonomic, functional and evolutionary substantive substructures. When explaining macroscopic phenomena, the atomic-molecular theory focuses on sub-microscopic entities such as atoms and molecules and their mechanisms of action (Vollebregt, 1998; Van Berkel, 1999) and is considered a key area in the field of chemical education. Another example of a substantive substructure from chemistry as a discipline would be thermodynamics, a research area which focuses exclusively on macroscopic magnitudes like P, V and T to the exclusion of microscopic models while searching for explanations. Second, substantive substructures are not only elaborated on during the course of enquiry, but also tested and, eventually, revised. Third, the scientific knowledge gained in terms of a substantive substructure stems from selected abstractions or idealisations of the subject matter or referent in question and is, therefore, always partial and incomplete.

Philosophical Substructures of the Disciplines

We use the term philosophical substructure of a curriculum (Van Berkel, 2005, pp. 33, 52), whereas Schwab uses the term syntactical or also methodological substructure. The philosophical substructure of a curriculum contains besides methodological assumptions a number of, often implicit, philosophical foundations of a curriculum.



Schwab (1964a, p. 14) describes the syntactical or methodological substructure of a discipline thus:

> ‘There is, then, the problem of determining for each discipline what it does in the way of discovery and proof, what criteria it uses for measuring the quality of its data, how strictly it can apply canons of evidence, and in general, of determining the route or pathway by which the discipline moves from its raw data through a longer or shorter process of interpretation to its conclusion’.

Further, Schwab (1964b, pp. 10, 11) emphasises that to each of the possible substantive substructures of a discipline there corresponds a distinctive syntactical substructure:

> ‘If different disciplines pursue knowledge of their respective subject fields by means of different substantive [sub]structures, it follows that there may be major differences between one discipline and another in the manner and the extent to which each can verify its knowledge (. . .). Further, the kind of evidence, and the degree to which it is evidential, required by different researches within the natural sciences differ markedly from field to field (biology against physics, for example) and even within researches within a field’.

In chemistry, for example, it is the case that the different substantive substructures of the atomic-molecular theory and thermodynamics correspond to different syntactical substructures in terms of ‘the manner and the extent to which each can verify its knowledge (. . .) the kind of evidence, and the degree to which it is evidential’ (Schwab, 1964b, p. 11).

This makes the philosophical substructures of a discipline also plural, as well as specific to the domain involved. As Schwab (1964b, p. 31) puts it,

> ‘Of greatest importance perhaps, in view of the present state of education in this regard, is that syntax effectively does away with the embarrassing divorce of “method” and “content”. A syntax cannot be described except through reference to the concrete subject matter involved in concrete enquiries’.

Pedagogical Substructure

Schwab discusses the *philosophical (syntactical)* substructure of the disciplines in education or pedagogy, listing and emphasising each time the educational significance of his concepts (Schwab, 1962, p. 205):

> ‘Both of these – the conceptual and the syntactical [philosophical] – are different in different disciplines. The significance for education of these diverse structures lies precisely in the extent to which we want to teach what it is true and have it understood’.

Schwab elaborates on the relationship between the (substantive) substructure of the discipline and the *pedagogical substructure* as follows (Westbury & Wilkof, 1978, pp. 241, 242):

> ‘We also have the task of learning to live with a far more complex problem – that of realizing that we will no longer be free to choose teaching methods, textbook organization, and classroom structuring on the basis of psychological and social considerations alone. Rather, we will need to face the fact that methods are rarely if ever neutral. On the contrary,

> the means we use color and modify the ends we actually achieve through them. *How* we teach will determine *what* our students learn. If a [sub]structure of teaching and learning is alien to the [sub]structure of what we propose to teach, the outcome will inevitably be a corruption of that content. And we will know that it is.'

The mix of pure chemistry and chemical–technological–societal concepts which Salters Chemistry used, de facto, coloured the students outcome, and before that, that of the teachers and developers.

The structure of a discipline does not have, as such, a pedagogical substructure, but it does *take on* a relationship to a pedagogical substructure. Thus, in education, the substantive and philosophical substructures of a discipline assume a specific relationship to the pedagogical substructure of a curriculum.

A coherent combination of these three substructures forms a curriculum structure.

Dominant School Chemistry

The responses of a forum of experts in chemical education in the 1990s (Van Berkel, De Vos, Verdonk, & Pilot, 2000) were analysed in terms of the curriculum framework outlined above. According to this analysis, the mainstream school chemistry curricula at that time, to be called 'dominant school chemistry', can be characterised as follows. With respect to the relation between *the philosophical substructure* and *the pedagogical substructure*, school chemistry often claims to position itself as an introduction to chemistry. The student is seen as a future chemist. However, the forum of experts in chemical education disagreed with this claim. The next quote epitomises the view that in fact this school chemistry gives an incorrect picture of chemistry as a science:

> 'We tend to teach chemistry by using certain well established standard items of dogma . . . theoretical propositional knowledge often dominates school chemistry and symbolic notation becomes a reified account of many facts which have never been observed[1]'.

Instead, in the current 'dominant school chemistry' curriculum, chemistry is being taught and learned as propositions and algorithms to students, still seen as future chemists.

With respect to the *substantive substructure,* respondents agreed that dominant school chemistry

- has a corpuscular theoretical focus on chemical substances and their properties and deals as such with micro–macro thinking;
- deals with the explanation and systematisation of chemical information largely in terms of corpuscular theory, i.e. the main focus is on describing the microworld of chemistry in terms of relationships between macroscopic properties and corpuscular models;

---

[1] See Van Berkel (2005) for details of the responses of the international forum and the Dutch forum.

- makes a distinction between a level of phenomena (macro) and a level of the corpuscular (micro). However, the introduction of corpuscular theory in books and classroom is neither consistent nor accurate, and hence not effective.

To further elaborate on this last point, it should be noted that once corpuscular theory is introduced it should provide students with meaningful descriptions, explanations and predictions of *macroscopic* phenomena and relationships in terms of *sub-microscopic* entities such as atoms, molecules and electrons. But, alas, according to the forum of experts in chemical education, it does not (Van Berkel et al., 2000). Not only students, but also teachers as well as textbook writers make mistakes with regard to the *macro/sub-micro/symbolic* levels. Here are some examples mentioned by the international and Dutch forum.

With Respect to Textbooks

The distinction between the macroscopical and microscopical levels of description certainly exists. However, it is not adequately stressed in school chemistry books. Indeed, the descriptive language used in these books does not maintain that distinction. Phrases such as ‘nitrogen has a triple bond’ illustrate the point: nitrogen is a colourless, odourless unreactive gas; the nitrogen *molecule* has a triple bond. The triple bond provides the explanation of the unreactive nature of the substance:

> ‘.. the particles of which the corpuscular theory speaks are often taken as the small(est) parts of a substance; and offer, because of that, no explanation of the phenomena’.

With Respect to Teaching

There are many examples of schoolbooks and teachers that do not distinguish between the two levels (phenomena and corpuscula) or, to say the least, that deal with them rather carelessly. Often language is used inaccurately, e.g. you speak of ‘iron’ when you should have spoken of ‘ions of iron’. It is often said that

> . . . a molecule is the smallest part of a substance which is still that substance (sic!)

With Respect to Student Learning

The corpuscular theory does provide explanations for phenomena but how far are these internalised by students? Many continue to reason in macroscopic terms about events, even after being taught corpuscular theory.

And another member of the forum wrote,

> . . . students ascribe properties of substance to particles: They melt, they grow etc.

What dominates school chemistry, as the following set of quotes again show, are corpuscular ideas on valency, bonding and structure, usually in a simplified way:

> ‘Valency, for *simpler* predictions only. Valency as an idea which *neatly* explains formulae for them’.
> ‘Important to recognize *limitations* of this concept [Lewis octet] in relation with the noble gas chemistry.’
> ‘*Simple* bonding theory and the carbon monoxide molecule!’
> ‘. . . what determines which reactions will be discussed is the *simplicity* of how atomic structure is involved’.
> ‘Corpuscular theory offers, for that matter, only a very *limited* basis for the explanation of macroscopic phenomena (. . .) sometimes it looks as if 1,2-dichloroethane is C2H4Cl2 (. . .)’.

This then leads to the situation that ‘students learn ‘tricks’ to deal with an invisible world (of molecules and atoms) which they have to accept on the basis of ‘authority’, not on the basis of evidence and argument (in relation to the *philosophical substructure*) as would be the case in an effective curriculum aimed at meaningful understanding. This dominant school chemistry curriculum fails to realise its own set goals of initiating and preparing future chemistry students by teaching them the theoretical understanding of chemical phenomena. As one respondent puts it,

> Not only does the theoretical approach make chemistry more difficult to understand, it also transforms it into a plugging of numbers into inaccurate formula for students to get answers to questions while understanding neither the question nor the answer.

Most respondents felt, as one of them expressed it, that

> the corpuscular character is an essential aspect of the explanatory theory and its predictions I was confronted with at secondary school: say, the theory of Dalton and the later developments, possible on its basis, such as ‘valency’, chemistry of ‘dashes’ and so on.

It is essential, therefore, many respondents agreed, to teach students the ability to distinguish clearly between the macro-level of phenomena and the micro-level of corpuscles, and more in particular, to teach them to think back and forth, i.e. in terms of the macro–micro relationships involved in corpuscular explanations.

Kuhn and ‘Normal Chemistry Education’

In a recent paper Schwartz (2006, p. 984) points to the contradiction between the nature of chemical research and the nature of traditional chemistry teaching:

> . . . [the] approach of engaging complex problems more closely approximates the methodology of scientific research than do the simplifications and idealizations of traditional science teaching.

Science, after all, is a process for interrogating nature, not simply a compendium of facts:

> . . . students [should be] exposed to the inquiring, experimental, and often tentative nature of science. . .. Moreover, our pedagogy [should] reintroduce ambiguity into the classroom and the teaching laboratory, where it most definitely belongs. Too many traditional science

> courses misguidedly protect students from the ambiguity that is part of the beauty and fascination of the natural world – a practice that particularly ill serves those who seek [or do not seek, we like to add] to become scientists.

This quotation, illustrating the key problematic feature of dominant mainstream (traditional) chemistry courses described above, can be interpreted in terms of Kuhn's theory of *normal science* and *normal science education*. Kuhn underpinned his theory of the dynamics of normal science with a less well-known theory on the structure and function of tertiary and secondary science education (Siegel, 1990). Kuhn's theory (1963, 1970a, 1970b, 1970c, 1977a, 1977b) is instructive to understand that there is specific view of science education which can be called, in Kuhn's vein, *normal chemistry education*, and that the dominant version of the school chemistry curriculum can be interpreted in this way.

Kuhn's paper, 'The Function of Dogma in Scientific Research', also contains a clear statement of his views on 'scientific pedagogy' (Kuhn, 1963, pp. 350, 351):

> The single most striking feature of scientific education is that, to an extent quite unknown in other creative fields, it is conducted through *textbooks*, works written especially for students. Even books that compete for adoption in a single course *differ mainly in level and in pedagogic detail, not in substance or conceptual structure* [the substantial substructure]. . . .apparently scientists agree, about what it is that every student of the field *must* know. That is why, in the design of a *pre-professional curriculum*, they can use textbooks instead of eclectic samples of research (italics Kuhn, 1963, p. 351).

Kuhn (1970a, pp. 182, 187) describes how paradigms are taught as exemplars, which he describes as standard examples shared by a community of (future) scientists, on which other (end-of-chapter) problems are modelled. Through a textbook's exemplars the student is initiated into the disciplinary matrix: current theory, methods, and criteria of a normal science. Kuhn's analysis of the structure of science textbooks, especially of the techniques of textbook presentation, leads him to the following conclusions:

> Except in the occasional introductions that students seldom read, science texts make little attempt to describe the *sorts* of problems that the professional may be asked to solve or to discuss the *variety* of techniques that experience has made available for their solution. Instead, these books exhibit, from the very start, concrete problem-solutions that the profession has come to accept as paradigms [as exemplars], and they then ask the student either with a pencil and paper or in the laboratory, to solve for himself problems very closely modelled in method and substance upon those through which the text has led him (italics Kuhn, 1963, p. 351).

The pedagogic function of the textbook presentation is to accomplish

> . . . a relatively *dogmatic initiation* into a *pre-established* problem-solving tradition that the student is neither invited nor equipped to evaluate (ibid p. 351).

It is equally revealing to see what, according to Kuhn, is *not* included, in science textbooks:

> The objective of a textbook is to provide the reader, in the most economical and easily assimilable form, with a statement of what the contemporary community believes it knows and of the principal uses to which that knowledge is put [Sub]. Information about *how*

> *that knowledge was acquired (discovery)* and about *why it was accepted by the profession (confirmation)* would at best be *excess baggage*. Though including that information would almost certainly increase the ‘humanistic’ values of the text and might conceivably breed more flexible and creative scientists, it would inevitably detract from the ease of learning the contemporary scientific language. To date only the last objective has been taken seriously by most writers of textbooks in the natural sciences (Kuhn, 1977b, p. 186).

Kuhn emphasises in various places that the ‘misdirection supplied by science texts is both systematic and functional’ (1977b, p. 187). The dogmatic initiation into a normal science tradition by creating among students a misleading picture of the nature of science, a *textbook image of science* as Kuhn calls it, enhances ‘the research efficiency of physical scientists’ (p. 187). This philosophical substructure of the curriculum can be termed as *educational positivism*, i.e. science is presented in the textbooks as an accumulation through induction of facts, laws and theories (see also Van Aalsvoort, 2004a). The systematic textbook presentation described by Kuhn will therefore initiate and prepare students for the handling of normal chemistry problems, i.e. for the activity of puzzle-solving as set within the current paradigm or disciplinary matrix, which is all that future normal chemist need in order to function successfully.

Thus, based on Kuhn’s view on science education, *normal chemistry education* stands for a specific view on chemistry (normal chemistry) in combination with a specific view of education i.e. the teaching of normal chemistry through textbooks-cum-exemplars to future chemists while using the current paradigm as a substantive substructure, presenting science as cumulative growth of facts. This is educational positivism.

To sum up, Dominant School Chemistry taken as the mainstream chemistry curriculum is characterised by a substantive substructure in the domain of micro–macro

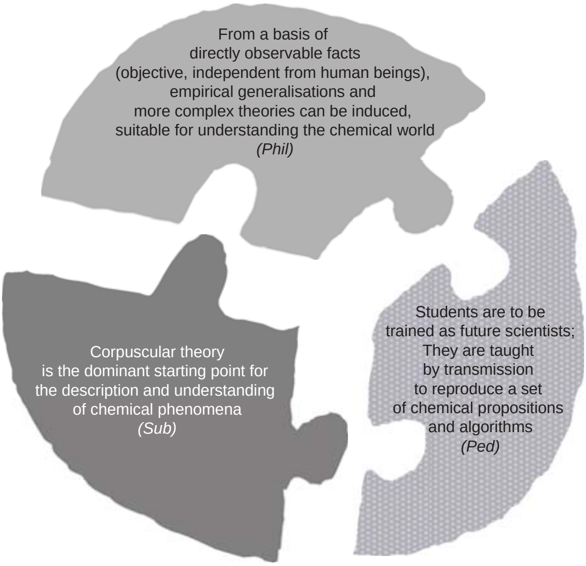


Fig. 2.3 The structure of Dominant School Chemistry consists of a combination of a specific substantive substructure: based on corpuscular theory, a specific philosophical substructure: educational positivism, and a specific pedagogical substructure: intended to provide the initiatory and preparatory training of future chemists

thinking, based on *corpuscular theory*, which is rigidly combined with a specific philosophical substructure, i.e. *educational positivism*, and a specific pedagogical substructure, i.e. *initiatory and preparatory training* of future chemists. The combination of the substantive, philosophical and pedagogical substructures of dominant school chemistry is summarised in Fig. 2.3.

Recommendations for Curriculum Development

How can the curriculum theory described above be useful in effectively applying the two strategies, connecting to daily-life experiences and updating chemical content, when trying to improve the meaningfulness of learning with respect to the relationship between macroscopic phenomena and the sub-microscopic world of atoms and molecules?

First, the strategies should address the problem of confusing messages of what is to be learned as a result of using different curriculum emphases within one unit of a curriculum. The interpretation of mainstream chemistry courses in Schwab's and Kuhn's terms show that a rather strong implicit consensus apparently has led to a rigid combination of the three substructures of school chemistry. When aiming to broaden the aims of school chemistry, i.e. to connect it to the lives of the majority of students, this obviously has consequences for the *pedagogical substructure*. Chemistry for citizenship, for example, differs from mainstream school chemistry regarding the aims for future chemical education. Activities should not – as a default activity – be directed towards a reproduction of chemical propositions and algorithms. Instead, activities should aim to have students experience a relation between phenomena that are of interest to their lives and the chemical content they learn. Similarly, the philosophical substructure changes: when school chemistry is to address daily-life and societal issues, the curriculum's philosophy can no longer be 'objective' without acknowledging that chemistry is embedded within human cultures and their societies. Therefore, in accordance with Schwab's theory also different concepts are part of the substantive substructure of the curriculum, for example the concept of risk assessment, and economic, ethical and political concepts.

It is important to understand why confusing messages occur. When, for example, the philosophical and pedagogical substructure change without reconsidering the content or at least the focus on corpuscular theory, an inconsistency between the substructures of school chemistry occurs. To quote Schwab again (Schwab, 1978, p. 242),

> '. . . If a [sub]structure of teaching and learning is alien to the [sub]structure of what we propose to teach, the outcome will inevitably be a corruption of that content'.

Such a mixing up of different curriculum emphases has been studied in depth by Van Berkel for the Salters' Science unit about 'Metals' (Table 2.1). The designers of the unit aimed at a 50 – 50 balance of pure chemical content (*Solid Foundation)* and chemical–technological–societal content (*Science, Technology and Decisions)*. Van

Berkel (2005) has analysed how during the process of development, revision and examination, this ratio has shifted into a much more heavy emphasis on Solid Foundation (pure chemical content). Some concepts which are not really needed to put across the emphasis *Science, Technology and Decisions*, are nevertheless developed (e.g. oxidation and reactivity series). Some important concepts are not developed, although they are needed for this emphasis (e.g. composition of metal objects, the process of chemical change, and order of corrodibility). This shift from ideal to realisation during curriculum development is described by Goodlad et al. (1979) as: 'slippage from any ideal formulation to what reaches the student'. When the message about what is why to be learned is unclear, curriculum designers, teachers and students tend to fall back on the default emphasis of *Solid Foundation*, analysed in this chapter as Normal Chemistry Education (cf. Hart, 2002 for physics education).

Over the years, in successive curriculum developments, content is simply added, instead of changing the substantive substructure in accordance with the philosophical and pedagogical substructure aimed at. This leads to the successive layers discussed above.

Using Schwab's framework, it becomes clear how school chemistry curriculum fails to realise its own set goals of initiating and preparing future chemistry students teaching them the theoretical understanding of chemical phenomena. The tendency is to add historical layers to the substantive substructure of the curriculum when 'updating' content calls for a higher degree of 'efficiency' within the time available for

Table 2.1 Overview, chemical unit Metals of Salters' Science (1989); Asterisks denote pure chemical (Solid Foundation) content; Italics denote chemical technological–societal (Science, Technology and Decisions) content (Van Berkel, 2005, p. 177)

This unit is concerned with:

- *the importance of metals,*
- *the relationship between the properties of metals and their uses,*
- *the problems of corrosion*.

The unit starts with a survey of *the surroundings* in which students familiarise themselves with the *names, *physical properties and *uses of common metals*. The *use of symbols to represent metals is also introduced. Discussion of the *physical properties which metals have in common then leads to the idea that *different metals can be identified by their chemical properties. Students complete *simple qualitative tests on known metals and *use these tests to identify metals in common objects.*

After this initial study of the *chemical properties of metals, *the processes of corrosion* and burning are investigated and this leads to an introduction of the terms *element, *compound and *reaction.

Students go on to investigate *rates of corrodibility* and *the reactivity series is introduced. *Methods to prevent rusting* are considered in a homework exercise and further opportunities to study *the methods of rust prevention* are provided in two optional lessons.

Work on corrosion allows further discussion of the *usefulness of metals*; the unit ends with a study of *alloys* in which *solder is prepared* and *the properties of alloys are related to their uses*.

teaching chemistry in school (but leads to an overloaded and confusing curriculum). Teaching chemistry has become ‘coverage’ of the chemistry curriculum, instead of a ‘discovery’ of chemical phenomena (Schwartz, 2006, p. 996). As different layers of content accumulate in school chemistry over the decades, these sedimentary structures become compressed into a set of corpuscular theories which at first hand may seem to offer an all-applicable generalised explanation for natural phenomena. However, a more in-depth study reveals inconsistencies in the use of concepts by developers, teachers and students. This accumulation into a survey curriculum tends to restrict the time available for scientific reasoning and constructivist pedagogical approaches.

Both effects of the two strategies are visualised in Fig. 2.4. Incoherency between the substructures of the curriculum is illustrated by those pieces of the jig-saw puzzle that do not fit together. The sedimentary layers, the accumulation of chemical theory, and subsequent curriculum overload are visualised with the layers of the substantive substructure that leads to a huge outgrowth.

This overview communicates two important messages. Changing only one piece of the puzzle is not enough: the curriculum needs to be changed in all three substructures simultaneously in order to connect to daily-life experiences and to socio-

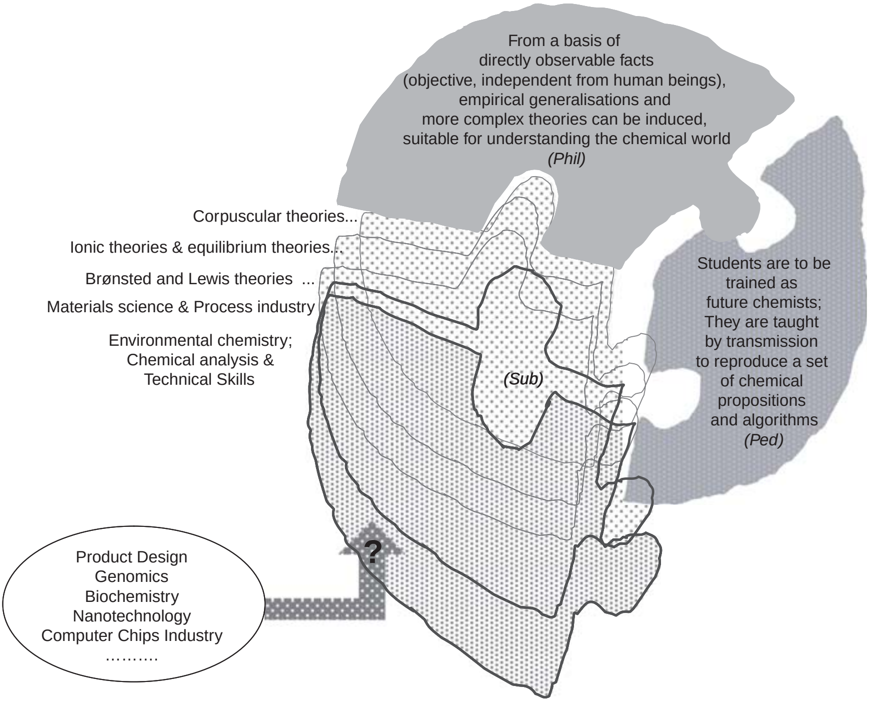


Fig. 2.4 An overloaded chemistry curriculum with a sedimentary structure according to De Vos and Pilot (2001), interpreted with the three substructures of the dominant version of mainstream chemistry courses according to Van Berkel et al. (2000)

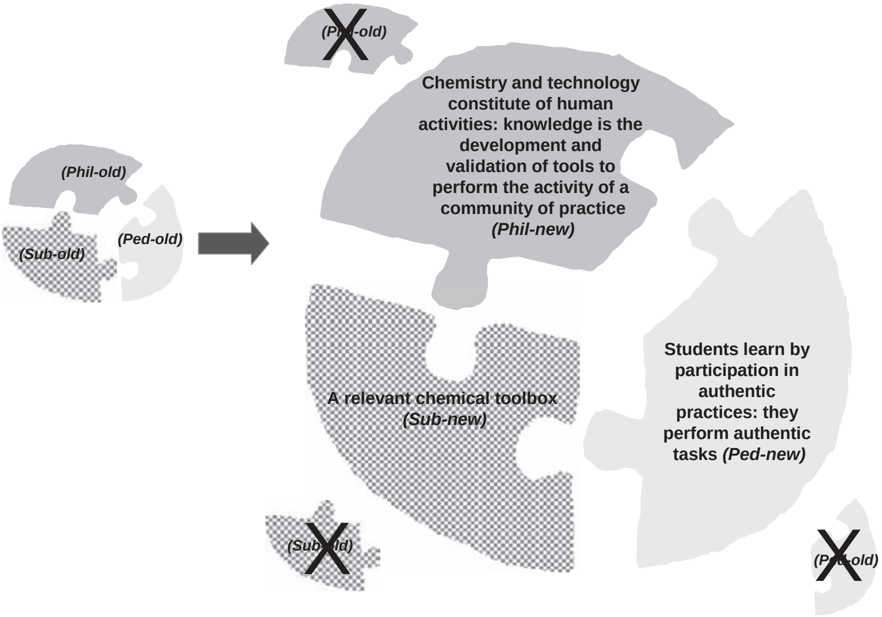


Fig. 2.5 A new coherent relationship between philosophy, pedagogy and scientific content needs a co-ordinated change in all three substructures

scientific issues. Secondly, contemporary developments of material science and technology ‘*on top of*’ the existing substantive substructure of the curriculum evidently will further overload the curriculum leaving even less time available for a genuine and coherent exploration of the philosophical and pedagogical substructure of school chemistry. Therefore, at the secondary level, the initiation into normal chemistry should be largely replaced by an education in or through fluid, critical, or creative chemistry, together with an education in or about the relations between chemistry, technology, and society. For an escape from Normal Chemistry Education, a *co-ordinated replacement* of the currently rigid combination of substantive, philosophical, and pedagogical substructures of school chemistry will be necessary (cf. Fig. 2.5, which is explained further below).

How to Escape

The recommendations in the preceding section are part of a systematic strategy to escape from the dominant version of the mainstream chemistry curricula, characterised as Normal Chemistry Education, in terms of a framework for analysis, development, and design-based research. But before presenting this strategy we summarise the argumentation in three conditions for escape and some of the implications involved (Van Berkel, 2005).

Condition one: *In order to escape, we have to know what to escape from.*

- Perform a domain-specific analysis of the nature and structure of the dominant school chemistry curriculum in terms of a combination of the dominant substantive, philosophical and pedagogical substructures.

With respect to the core concepts of micro–macro thinking in chemistry education, this has been presented in the preceding sections using the curriculum theories of Schwab and Kuhn. Local or national circumstances may be slightly different, and these need to be part of the analysis, although mainstream chemistry curricula are rather similar from an international perspective.

Condition two: *In order to escape, we have to know what to escape to.*

- Aim towards a coordinated replacement of the currently dominant (rigid) combination of substantive, philosophical, and pedagogical substructure of school chemistry.
- Develop and legitimise a new curriculum emphasis for school chemistry, in terms of a new coherent combination of a substantive, philosophical and pedagogical substructure.
- Use the concepts of Curriculum Emphases and the framework of Normal Chemistry Education as instruments to articulate the new vision on the chemistry curriculum in terms of design criteria, i.e. a new conjectural vision to be operationalised by the design of exemplars of the teaching material in the formal (designed) curriculum.

Condition three: *In order to escape, we have to know how to escape.*

- Be aware of, anticipate and avoid the Normal Chemistry Education reflex, i.e. the introduction into design and teaching of more chemical concepts than are needed for the chosen curriculum emphasis. Alternatively, deal in time with any difficulties related to the dominant school chemistry curriculum at all stages of development, starting with the initial vision and the first design of the curriculum.
- Collect evaluation data at all stages of development to safeguard the adopted vision, in moving from the vision all the way to the implementation of the curriculum in the classroom.
- Check the newly chosen curriculum emphasis, articulated in the vision on the curriculum in terms of design criteria, for consistency at all stages of curriculum development.

Conditions two and three can only be fulfilled in iteration using Schwab's substructures of a curriculum (*Phil* – *Ped* – *Sub*). The main question is how to start the iteration. To work out a new vision on the learning of micro–macro thinking, there needs to be an interrelation between chosen philosophies on chemistry (education; *Phil*) that is consistent with a pedagogical theory (*Ped*). An example is extensively described by Meijer, Bulte, & Pilot (2005; see also Pilot et al. in this book): chemistry is considered as a human activity in relevant communities of practice (*Phil*), while learning (*Ped*) is to take place as participation in such (situated) communities of practice. To avoid the use of the traditional conceptual structure (a Normal Chemistry Education reflex), an appropriate substantive substructure of micro–macro thinking (*Sub*) needs rethinking. It is best advised to start from the new vision on the curriculum with an authentic, relevant task as a context (Bulte et al., 2005). Developers and teachers who are not familiar with the new vision will otherwise inevitably fall back to the prevailing content of atoms and molecules first (*Sub – old*; Fig. 2.5). Consistent with the choice for communities of (social) practice, and the learning by participation, the replacement of content (*Sub*) can be based on the discourse of the related social practices. This means that an analysis is needed of how experts discuss and think when addressing authentic tasks belonging to selected social practices related to chemistry. Much of the (new) substantive substructure (*Sub – new*) will be implicit or tacit in nature, as it has never been made explicit or considered important in the present substantive substructure (*Sub – old*; Fig. 2.5 and more extensively in Pilot et al. in this book; also Van Aalsvoort, 2004b). The starting point is, because of this argument, to develop criteria for selecting authentic tasks for redefining the substantive substructure of the curriculum. Each new team of developers should develop these when constructing a new curriculum which is appropriate for the local circumstances, the age of the students, and the aims of chemistry education (preparation for future education, chemistry for all, etc.).

The example given here (Fig. 2.5; and in Chapter 9) is only presented as an illustration. Many other philosophies of science and theories of learning exist, can be brought into agreement with each other and inevitably will lead to another redefinition of the substantive substructure. Within one programme, even a pallet on different choices may exist, e.g. an emphasis on *Science, Technology and Decisions* in one unit and an emphasis on *Structure of Science* in a second unit. However, Roberts' message not to mix up curriculum emphases within one unit is to be taken as a leading design principle.

Developing a new vision is the necessary first stage. However, developing an entire consistent curriculum based on a new vision involves several steps that are impossible to take in one single pathway in order to fulfil the conditions two and three. Transformation directly into a whole new set of curriculum materials would involve the design of a tremendously large number of curriculum materials, with large investments in human resource and time. Using Goodlad's model of curriculum representations (Goodlad et al., 1979; Van den Akker, 1998), a design process for a new curriculum can be visualised in Fig. 2.6. This design process consists of six elements (see also Gilbert, 2006; Van Berkel, 2005):

- The visionary curriculum: the original vision, basic philosophy, rationale and mission underlying it.
- The formal curriculum: the elaboration of the original version in the documentation about the course that will be made widely available. All design teams produce such paperwork with design criteria, student materials and teacher materials (for that reason also called the designed curriculum).
- The perceived curriculum: how teachers, the main users of the formal curriculum, understand what it intends and implies.

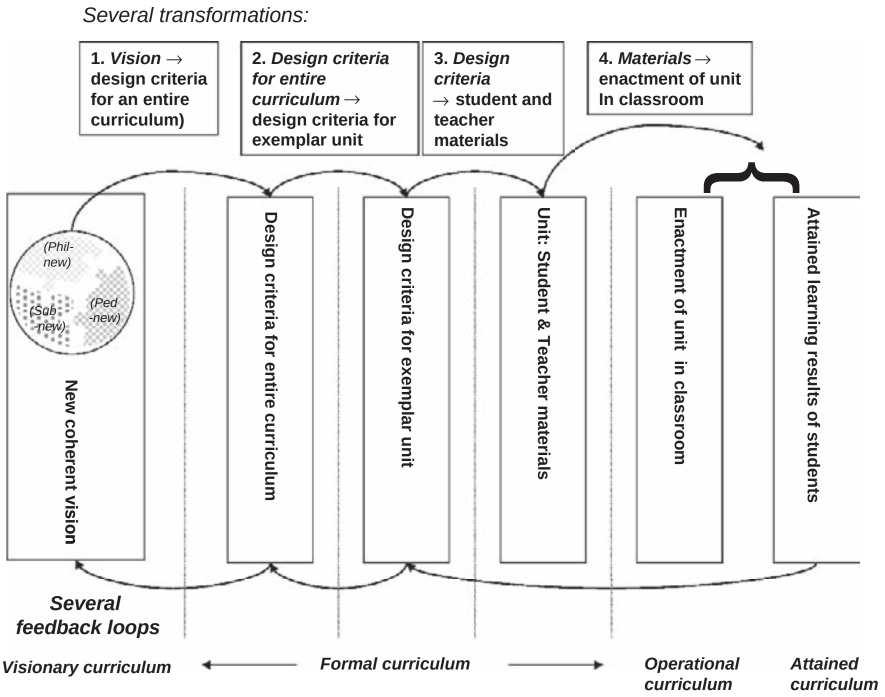


Fig. 2.6 Transformations from a vision on chemistry education into design criteria for an entire curriculum (1), into an exemplary unit (2), into students and teacher materials (3), into the operational form in a real classroom, into attained learning results of students (4). The arrows in the lower part of the figure represent evaluative feedback loops of the transformations

- The operational curriculum: the nature and content of the interactions between teachers, students, and resource materials, which take place in the classroom.
- The experiential curriculum: the actual learning processes that the students undertake.
- The attained curriculum: the learning outcomes achieved by the students, as recorded in the results of their assessment.

According to Van den Akker (1998, p. 422),

> "This typology of curriculum representations is particularly instructive for analysing the roots and fruits of numerous curriculum innovations efforts in science education over the previous decades. Curriculum reform typically is aimed at reducing the incongruence between 'new' ideas and current student learning."

In other words: when a new coherent vision is to reduce the experienced lack of meaningfulness when students learn about atoms and molecules (cf. Osborne & Collins, 2001), eventually this vision (visionary curriculum) should be reflected in the operational, experiential and especially the attained representation of the curriculum. Therefore, the further fulfilment of conditions two and three implies an iterative process which also involves a scaling-up that is possible only when in earlier transformations the attainment of the set of criteria is realised. Maintaining consistency of vision across all curriculum representations is supported by evaluative feedback loops in order to avoid 'slippage': incongruence between the vision and what reaches the student (Goodlad et al., 1979; see also Van Berkel, 2005, p. 176).

General criteria are firstly further transformed into a single representative exemplar unit (formal curriculum; Fig. 2.6). The unit should be transformed into materials (formal curriculum; Fig. 2.6), which will be evaluated in real classrooms with real teachers and students (operational curriculum). The attained learning results are evaluated and related to the intentions described as learning aims for the exemplar unit (have students attained the learning aims for this exemplar unit as an example of the intentions described in the new vision?). The design of an exemplar unit takes place through a design research approach (Bulte, Westbroek, De Jong, & Pilot, 2006; Van den Akker, Gravemeijer, McKenney, & Nieveen, 2006; Pilot et al. in this book). During the design process, continuous evaluation and revision lead to an improved unit. Simultaneously, adjustment between criteria, design characteristics and the actual operational unit must be achieved. Finally, a successfully developed unit must meet the essential criteria. A careful analysis of the exemplar unit provides a basis for adjustment and sharpening of a new vision on chemistry education. This is underlined by the *feedback* arrows at the bottom of Fig. 2.6, thereby showing the checks on consistency in the development of the unit.

The exemplar unit must also make it easier to communicate a new vision on chemistry education to all actors and stakeholders. A vision described in abstract terms (as is necessary in this stage of development) is difficult to comprehend and discuss. An exemplar evaluated in real classrooms can then be used as a concrete illustration of a new vision. Once agreement has been reached upon this point, curriculum development can take place at a larger scale.

The following six questions can be regarded as guidelines for development of a new vision on macro–micro thinking in chemistry education:

1. What is the content and focus of a new vision on the chemistry education curriculum in terms of the three coherent substructures discussed above that should lead to meaningful learning of micro–macro thinking?
2. Is this vision effectively and correctly transformed into design criteria for the formal representation of a curriculum (are the criteria valid, precise and complete; transformation 1)?
3. What are the characteristics of designed units about the domain of micro–macro thinking, leading to units within which design criteria are realised (transformations 2 & 3)?
4. Is the theme chosen for the exemplar unit appropriate to make this unit a representative example for micro–macro thinking regarding the substantive substructure (evaluative feedback formal → visionary curriculum)?
5. Does the unit have a philosophical substructure such that students indeed experience their micro–macro thinking as meaningful (evaluative feedback attained → visionary curriculum)?

6. Does the unit have a pedagogical substructure such that students indeed attain a coherent mental map about micro–macro thinking (evaluative feedback attained → visionary curriculum)?

In such a way, a tentative but continuous design process should lead to unit exemplars that meet the three conditions for escape. These units should exemplify the key part of a chemistry curriculum about micro–macro thinking, with coherence between the philosophical, pedagogical and substantive substructure. In the chapter by Pilot et al. in this book, a first step is described towards such a macro–micro unit using a design research approach. For other examples of units we refer to Van Aalsvoort (2004b), Bulte et al. (2005), Westbroek (2005) and Prins et al. (2008). All these studies attempt to escape from the overview curriculum with all the chemical theories that have been developed in the last century.

When the body of knowledge in chemistry and chemical technology evolves, chemistry education needs to develop new answers to meet the future standards for challenging and inspiring curricula, for future students and citizens who are intrigued by the material world. Societal development such as genomics, the influences of nanotechnology and the requirements for sustainable development deserve such new answers. The questions hopefully are raised by the analysis described in this chapter.

References

Bennett, J., & Holman, J. (2002). Context-based approaches to the teaching of chemistry: What are they and what are their effects? In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 165–184). Dordrecht, the Netherlands: Kluwer Academic Press.

Bennett, J., & Lubben, F. (2006) Context-based chemistry, the salters approach. *International Journal of Science Education, 28*(9), 999–1016.

Bennett, J., Lubben, F., & Hogarth., S. (2007), Bringing science to life: A synthesis of the research evidence on the effects of context-based and STS approaches to science teaching. *Science Education, 91*, 347–370.

Bulte, A. M. W., Klaassen, C. W. J. M., Westbroek, H. B., Stolk, M. J., Prins, G. T., Genseberger, R., et al. (2005). Modules for a new chemistry curriculum, research on a meaningful relation between contexts and concepts. In P. Nentwig & D. Waddington (Eds.) *Making it relevant. Context-based learning of science* (pp. 273–299). Munster: Waxmann Verlag.

Bulte, A. M. W., Westbroek, H. B., De Jong, O., & Pilot, A. (2006). A research approach to designing chemistry education using authentic practices as contexts. *International Journal of Science Education, 28*(9), 1063–1086.

De Vos, W., & Pilot, A. (2001). Acids and bases in layers: The stratal structure of an ancient topic. *Journal of Chemical Education, 76*(4), 528–530.

De Vos, W., Bulte, A. M. W., & Pilot, A. (2002). Chemistry curricula for general education: Analysis and elements of a design. In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 101–124). Dordrecht, The Netherlands: Kluwer Academic Press.

Driessen, H. P. W., & Meinema, H. A. (2003). *Chemistry between context and concept, designing for renewal.* (http://www.nieuwescheikunde.nl/international/). Enschede: SLO.

Gilbert, J. K. (2006) On the nature of ‘context’ in chemical education. *International Journal of Science Education, 28*(9), 957–976.

Goodlad, J. I. et al. (1979). *Curriculum inquiry: The study of educational practice*. New York: McGraw-Hill.

Hart, C. (2002). Framing curriculum discursively: Theoretical perspectives on the experience of VCE physics. *International Journal of Science Education, 24*(10), 1055–1077.

Hoffmann, R., & Coppola, B. P. (1996) Some heritical thoughts on what our students are telling us. *Journal of College Science Teaching*, 390–394.

Kuhn, T. S. (1963) The function of dogma in scientific research. In A. C. Crombie (Ed.), *Scientific change* (pp. 347–395). London: Heinemann.

Kuhn, T. S. (1970a). *The structure of scientific revolutions* (2nd, 1st ed., 1962). Chicago: University of Chicago Press.

Kuhn, T. S. (1970b). Logic of discovery or psychology of research? In I. Lakatos & A. Musgrave, *Criticism and the growth of knowledge* (pp. 1–23). London: Cambridge University Press.

Kuhn, T. S. (1970c). Reflection on my critics. In I. Lakatos & A. Musgrave, *Criticism and the growth of knowledge* (pp. 231–278). London: Cambridge University Press.

Kuhn, T. S. (1977a). The essential tension: Tradition and innovation in scientific research (first published, 1959). In T. S. Kuhn, *The essential tension* (pp. 225–239). Chicago: University of Chicago Press.

Kuhn, T. S. (1977b). The function of measurement in modern physical research (first published, 1961). In T. S. Kuhn, *The essential tension* (pp. 178–224). Chicago: University of Chicago Press.

Meijer, M. R., Bulte, A. M. W., & Pilot, A. (2005). *A conceptual analysis of micro-macro thinking – Using structure-property relations in chemical education*. Paper presented at the ESERA conference, Barcelona, Spain.

Meijer, M. R., Bulte, A. M. W., & Pilot, A. (in this book). Structure-property relations between macro and micro representations: Relevant meso-levels in authentic tasks. In John K. Gilbert & David F. Treagust (Eds.), *Multiple representations in chemical education*, pp. 195–214.

Osborne, J., & Collins, S. (2001), Pupils’ views of the role and value of science curriculum: A focus-group study. *International Journal of Science Education, 23*(5), 441–467.

Parchmann, I., Graesel, C., Baer, A., Nentwig, P., Demuth, R., Ralle, B., & the ChiK Project Group (2006). ‘Chemie im Kontext’: A symbiotic implementation of a context-based teaching and learning approach. *International Journal of Science Education, 28*(9), 1041 – 1062.

Pilot, A., & Bulte, A. M. W. (2006). The use of “contexts” as a challenge for the chemistry curriculum: Its successes & the need for further development and understanding. *International Journal of Science Education, 28*(9), 1087–1112.

Prins, G. T., Bulte, A. M. W., Driel, J. H., & Pilot, A. (2008). A selection of authentic modeling practices as contexts for chemistry education. *International Journal of Science Education, 30*(14), 1867–1890.

Roberts, D. A. (1982). Developing the concept of “curriculum emphases” in science education, *Science Education, 66*(2), 243–260.

Roberts, D. A. (1988). What counts as science education? In P. F. Fensham (Ed.), *Development and dilemma’s in science education* (pp. 27–54). London: The Falmer Press.

Schwab, J. J. (1962). The teaching of science as enquiry. In J. J. Schwab & P. F. Brandwein (eds.), *The teaching of science* (pp. 1–104). Cambridge, Massachusetts: Harvard University Press.

Schwab, J. J. (1964a). The structure of the natural sciences. In G. W. Ford & L. Pugno (Eds.), *The structure of knowledge and the curriculum* (pp. 1–31). Chicago: Rand McNally.

Schwab, J. J. (1964b). Problems, topics and issues. In S. Elam (Ed.), *Education and the structure of knowledge* (pp. 4–47). Chicago: Rand McNally.

Schwab, J. J. (1978). Education and the structure of the disciplines. In I. Westbury & N. J. Wilkof (Eds.), *J.J. Schwab: Science, curriculum and liberal education, selected essays* (pp. 229–273). Chicago: University of Chicago Press.

Schwartz, A. T. (2006). Contextualised chemistry education: The American experience, *International Journal of Science Education, 28*(9), 977–998.

Siegel, H. (1990). *Educating reason: Rationality, critical thinking and education.* New York: Routledge.

Van Aalsvoort, J. (2004a). Logical positivism as a tool to analyse the problem of chemistry's lack of relevance in secondary school chemical education. *International Journal of Science Education, 26*(9), 1151–1168.

Van Aalsvoort, J. (2004b). Activity theory as a tool to address the problem of chemistry's lack of relevance in secondary school chemical education. *International Journal of Science Education, 26*(13), 1635–1651.

Van Berkel, B. (1999). Uncommon, unnatural and unknown. *Tijdschrift voor Didactiek der Betawetenschapppen, 16*(1), 27–38.

Van Berkel, B. (2005). *The structure of current school chemistry – a quest for conditions for escape*. (PhD dissertation), Utrecht: Utrecht University, the Netherlands.

Van Berkel, B., De Vos, W., Verdonk, A. H., & Pilot, A. (2000). Normal science education and its dangers: The case of school chemistry. *Science & Education, (9)*1–2, 123–159.

Van den Akker, J. (1998). The science curriculum: Between ideals and outcomes. In B. Fraser & K. Tobin (Eds.), *International handbook of science education* (pp. 421–447). Dordrecht, The Netherlands: Kluwer Academic Press.

Van den Akker J., Gravemeijer, K., McKenney, S., & Nieveen, N. (Eds.) (2006). *Educational design research.* London: Routledge.

Vollebregt, M. J. (1998). *A problem posing approach to teaching an initial particle model.* PhD dissertation, Utrecht University, the Netherlands, Utrecht.

Westbroek, H. B. (2005). *Characteristics of meaningful chemistry education, the case of water quality.* (PhD dissertation), Utrecht: Utrecht University, The Netherlands.

Westbury, I., & Wilkof, N. J. (Eds.), (1978) *J.J. Schwab: Science, curriculum and liberal education, selected essays* (pp. 229–273). Chicago: University of Chicago Press.

Chapter 3
Towards a Better Utilization of Diagrams in Research into the Use of Representative Levels in Chemical Education

Maurice Cheng and John K. Gilbert

Abstract The representation of chemical concepts – indeed scientific concepts generally – is inherently multimodal, i.e. it involves the combination of more than one mode of representation. Consequently, the successful learning of chemistry involves the construction of mental associations among the macroscopic, microscopic and symbolic levels of representation of chemical phenomena using different modes of representation. Traditional linguistically framed research studies are only capable of capturing some aspects of that understanding. We suggest that students' understanding of diagrammatic representations – the visual mode – should be more extensively exploited in chemical educational research. Studies that have probed students' understanding through their construction of and through their interpretation of presented diagrams are reviewed. Further potential of the use of the visual mode of representation in such research, especially in respect of the macro/sub-micro/symbolic representational triplet, is also discussed.

The Multimodality of Scientific Knowledge

The use of diagrammatic representations in professional scientific journals, school science textbooks, newspapers and popular magazines is now very common. They have become an essential element in conveying scientific information from expert scientists to audiences of school students and the general public. Given their prominent role in scientific communication and in the learning of science, it is surprising that their roles have not been addressed more systematically and abundantly in scholarly discussions. Kress and van Leeuwen (2006) ascribe this negligence to the overt focus on verbal language in society that has led to a devaluation of the affordances offered by the visual mode of communication. In an empirical study of book chapters and papers published in some major scientific journals, Lemke (1998) found that diagrams are ubiquitous. In contrast to the commonplace belief that there exists one-to-one correspondences between a text and a diagram, scientific meaning

---

M. Cheng (✉)
The University of Reading, Reading, Wokingham RG6 6FN, UK
e-mail: mwcheng@hkucc.hku.hk

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_4,

is most commonly made by the ‘joint co-deployment’ of two or more modes of representation with one text. Lemke (1998) has succinctly expressed how different modes are used to express scientific concepts,

> ‘Concepts. . . are not defined by the common denominator of their representations, but by the sum, the union of meanings implied by all these representations. . . . It is the nature of scientific concepts that they are semiotically multimodal. . .’ (pp. 110–111).

As science concepts are multimodal in nature, it follows that the outcomes and processes of teaching science should follow in the same vein.

Kress, Jewitt, Ogborn, and Tsatsarelis (2001) have investigated how the teaching of science is achieved by multimodality. From this perspective, external representation in a visual mode (often called ‘visualization’) is regarded as more than a tool for learning. Rather, it enables learners to make meanings or express their ideas which they cannot readily do in the other modes of communication e.g. the verbal. In the communication of science, different modes have their different inherent affordances and address different specialized tasks. It is the combined effects of the different modes that realize the meaning intended by the authors of a text or by teachers (Kress et al., 2001, p. 14). This combined effect means that each mode multiplies the complexity of meaning achieved; each mode interacts with and contributes to the meaning derived from the others. Such interaction of modes can take different forms: sometimes different modes may carry the similar meaning; sometimes they may be complimentary by representing different aspects of meaning; at times they may even be contradictory.

The notion of a contradiction between modes needs some elaboration. Given the emphasis of ‘coherence’ in the epistemology of science, it might be surprising to find that different modes of representation provide contradictory information. However, such a contradiction is common, for example in the ‘particulate’ drawings that are used in chemistry and chemical education. Thus, it is not feasible to represent the percentage of dissociation of a weak acid within the scope of a diagram in such a way as to accurately reflect what is expressed mathematically. In Fig. 3.1, although Alternative (B) is regarded as the best illustration, if it were to be translated into mathematical data, the percentage of dissociation of HF would then be 20%[1]!

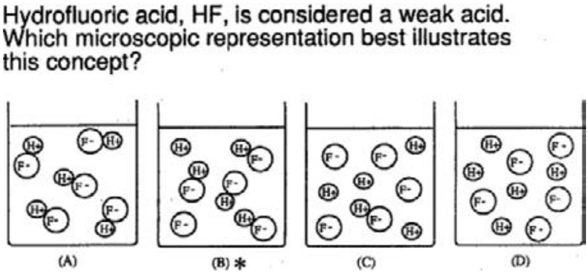


Fig. 3.1 An instrument used by Smith and Metz (1996) which probed students understanding of diagrammatic representation of a weak acid

---

[1] According to Stark and Wallace (1982), the p*K*a of HF is 3.25 (p. 74). The percentage of dissociation of a molar solution of HF would be 2.37%; and that of 0.1 M would be 0.75%.

Another common example where we find contradictory information provided by different modes is in the representation of the relative size of an atom and its nucleus. Again, diagrammatic representation can hardly do justice to the precise size of an atomic nucleus as compared with that of an atom as a whole. All diagrams in school science textbooks seem to exaggerate the nuclear size within an atom. Nevertheless, it is the numerical data (symbolic mode) or a verbal analogy (verbal mode, such as the analogy between the relative size of a tennis ball and a football field as compared to that of a nucleus and an atom) that can more accurately describe their relative sizes. It should be noted that although the information represented in the visual mode is not consistent with the other modes, what is important is that students should understand the nature of multimodal representations, and be able to inter-relate different modes of representation in arriving at the consensus meaning of scientific concepts.

Probing Students' Understanding of Chemistry from a Multimodal Perspective

In this section, we show how the multimodal perspective of scientific knowledge would shed light on our understanding of students' conceptions and difficulties when learning chemistry.

Beyond Linguistically Framed Research on Students Understanding of Chemistry

By 'linguistically framed research', we mean the kind of research studies which investigate students' understanding of chemistry solely via the verbal mode of representation. As we discussed in the previous section, different modes of communication make meaning differently, so the verbal mode alone can only express part of the meanings of chemical concepts. We must therefore probe into students' understanding of the visual mode through graphs, diagrams and photographs and charts. Also, besides studying how learners make meaning from individual modes of representation, it is also valuable to know how learners construct meaning through the interactions of different modes. In the next two sections, we will report an indicative review of some of the studies conducted so far that have utilized visual mode of representation as a probe into students' knowledge.

The Meaning of 'Not Being Able to Learn Chemistry Meaningfully'

The literature in science education in the past two decades or so has had a focus on student's understanding of science, not least in chemistry (Fensham, 2001). There are two inter-related interpretations of students' failure of grappling with established content knowledge:

(i) students are not able to link their existing knowledge with new information and/or do not have adequate pre-requisite knowledge (Garnett, Garnett, & Treagust, 1990; Nakhleh, 1994);

(ii) students are not able to inter-relate the macroscopic, microscopic and symbolic levels of representation (Gabel, 1998). For example, it has been found that students' success in balancing equations does not guarantee their accurate representation of the corresponding chemical reaction in a diagrammatic form (Yorroch, 1985). Our interpretation of these findings is that being able to balance chemical equations is about the understanding of the symbolic level, yet the ability to draw accurately is about the understanding of sub-microscopic level expressed through the diagrammatic mode of representation. Unsuccessful learning is thus interpreted in terms of students' difficulties in relating the two levels of representations to each other.

It has been widely reported that many students could correctly answer conventional examination-type questions yet they do not demonstrate genuine conceptual understanding upon further probing (Nurrenbem & Pickering, 1987). Similarly, many students were able to solve mathematical or algorithmic problems without being able to solve conceptual problems. While we believe that some students might rote-learn chemistry content knowledge and hence are not able to answer questions which demand deeper understanding, it is possible that they are not familiar with or are not able to mentally switch between different modes of representation. For example, in the study conducted by Smith and Metz (1996), it was found that many first year undergraduates were able to define 'strong acid' as being 100% ionized or dissociated. However, only 46.6% of them were able to choose a diagram (Fig. 3.2) that represents the sub-microscopic level of hydrochloric acid.

Our interpretation of the finding from the study is that even within a single level of representation, i.e. sub-microscopic, some students were unable to translate between different modes of representation. In this case, there was evidence that students were unable to translate their verbal mode of understanding into the diagrammatic mode (or visual mode). If the translation between different modes within the same level is problematic, it would be very challenging when students are required to smoothly mentally move about and link all the three – the macro, the sub-microscopic and symbolic levels – of chemical phenomena.

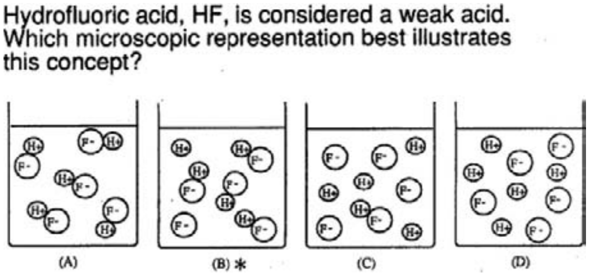


Fig. 3.2 An instrument which probed students understanding of diagrammatic representation of a strong acid (Smith & Metz, 1996)

In light of the above findings and interpretations, we suggest that students' difficulties in understanding chemistry can be expressed, besides (i) and (ii) mentioned above, as,

(iii) students do not understand the different modes of representation of physical phenomena and;
(iv) students are not able to translate and relate the different modes of representation.

These two difficulties are not only relevant from the multimodal learning perspective, but also relate to the 'meta-visualization' capability put forth by Gilbert (2008). In short, this involves at least the capability to,

- demonstrate an *understanding* of the 'convention' for different levels (i.e. macroscopic, sub-microscopic and symbolic) and dimensionality (3D, 2D and 1D) of representations.
- demonstrate a capacity to *translate* between different levels and modes of representation. As the information presented in different modes can be contradictory (see earlier in this chapter), a competent reader should be able to spot inconsistencies between modes and to make meaning selectively from valid information.
- demonstrate a capacity to be able to *construct* a representation within any level and dimensionality for a given purpose.

Within this framework, students' difficulties in understanding some chemistry concepts can be ascribed to their lack of meta-visualization capability in *understanding* and *translating* different modes of representation.

Research into Visualization Skills in School Sciences

Several research studies have probed students' interpretation, understanding and use of diagrams. For example, Stylianidou, Ormerod, and Ogborn (2002) investigated how students interpret textbook diagrams in the topic of 'Energy', Viennot and Kaminski (2006) looked into how minor changes in diagrams could have significantly affected students' responses to an assessment instrument. Reiss and Tunnicliffe (2001) asked students to draw what they perceived to be their organs and systems within the body. Pozzer and Roth (2003, 2005) have studied both the functions of photographs in biology textbooks and how students made sense of these photographs along with the associated captions and texts.

In chemistry, perhaps because of the significance in visualizing molecular structure, there has been a focus on how students perceive three-dimensional objects from a two-dimensional representation and how students mentally manipulate rotated, reflected and inverted objects (Stieff, 2007; Tuckey & Selvaratnam, 1993). Although these visualization skills are very important in chemistry, it is evident that they are not the only ones needed in school chemistry (Mathewson, 1999). For example, conceptual understanding of nature of different types of chemical bonding, atomic theory in terms of the Democritus particle model and the Bohr model, and stoichiometry, do not need these visualization skills. Rather, they involve the understanding of representational conventions, such as the meaning of 'arrows' used in diagrams, and how the verbal or mathematical mode of representation relates to and is translated into the visual mode.

The representation of some physical processes (e.g. the movement of electrons during electrolysis or in electrochemical cells) or industrial processes (e.g. Haber process), is predominately through the use of diagrams in textbooks and teaching aids. Instead of explicitly invoking the skills with which to mentally manipulate 3D molecular representations, readers of such texts have to identify the elements or the components of the diagrams, the movement of materials or chemical species and how they interact dynamically. We now highlight some of the research studies which touch on student's understanding of conventions and translation of various modes

Students' Understanding Probed Through Presented Diagrams

The Particle Model of Matter

Novick and Nussbaum (1978) explored students' understanding of the particle model of matter

(i) by asking students to draw diagrams of a gas at the sub-microscopic level and
(ii) by presenting diagrams to students that depict the particle model and the continuous model of matter and asking them to select one that was closest to their conception (See Fig. 3.3, for the representation before and after half of the gas is removed).

The role of the diagrams is pertinent to the present discussion: it was essential in the Novick and Nussbaum study. These diagrams probed into understanding of the following aspects of the particle model: (1) a gas comprises invisible particles. (2) Gas particles are evenly scattered in any enclosed space. (3) There is 'empty space' between the particles in a gas. (4) Particles in a gas are in intrinsic motion – they are not pushed externally. It would have been possible for students to rote-learn the above statements, so an investigation through a linguistically framed instrument would not have been able to fully explore students' understanding. For example, the idea of 'empty space' in statement (3) could have many different interpretations – all the options have 'empty space' between particles. It is only through the visual mode that the accepted view of the relationship between particles and empty spaces can be represented. It is only through the use of diagrams, a form of *external representation* and a form of representation alternative to textual description, that students' *internal representation* of particle model could be assessed with a higher validity.

Were the data harvested by Novick and Nussbaum (1978) still available, then based on the notion of multimodal learning (Kress et al., 2001) it would be revealing

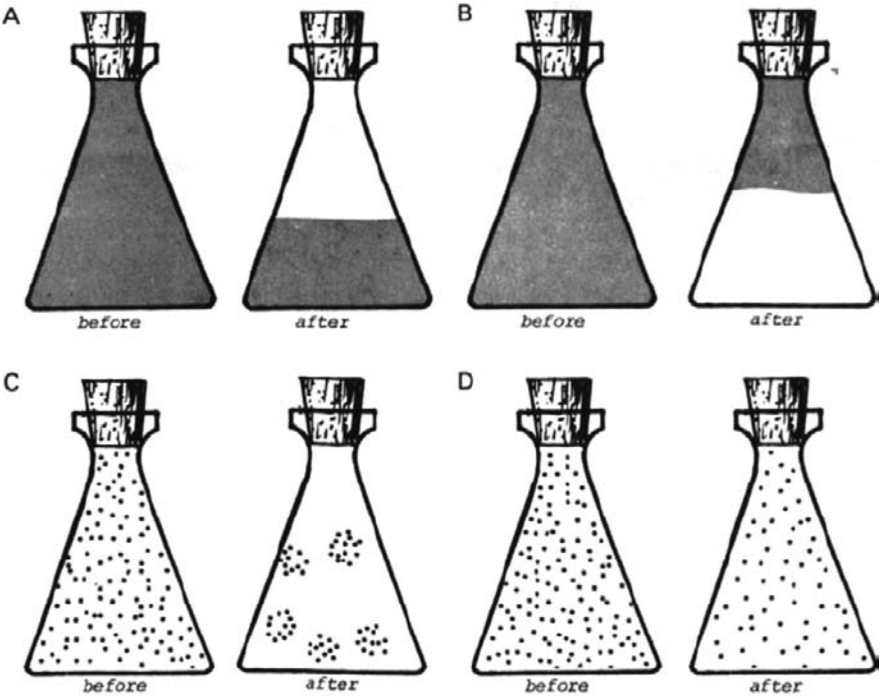


Fig. 3.3 Part of the diagrams presented to students in Novick and Nussbaum (1978, p. 279)

if the diagrams drawn by students were to be re-analyzed. For example, would students have thought that the particles have different forms or shape when half of the gas was removed? Also, other than the diagrams produced, how else could students draw a representation of their ideas that the distribution of gas particles is uneven? These are just a few ways in which the diagrams produced by students could be better utilized for research purposes. Like other studies of students' understanding of chemical and other scientific concepts, the deeper we delved into the data, the more insight we can gain into students' ideas and the easier it becomes to reveal unsuspected understandings. In short, we would like to emphasize the potential of analyzing students' drawings and the use of diagrams when investigating students' *internal representations* of scientific ideas.

Atomic Structure

Whether the Bohr atomic model or the quantum mechanical model is introduced to students, it is inevitable that they have to learn, among other things, that (i) the atomic nucleus is surrounded by electrons and (ii) most of an atom is empty space. Students' understanding of the visual representation of the above two statements was explored by Harrison and Treagust (1996). In the study, 48 Grade 8–10

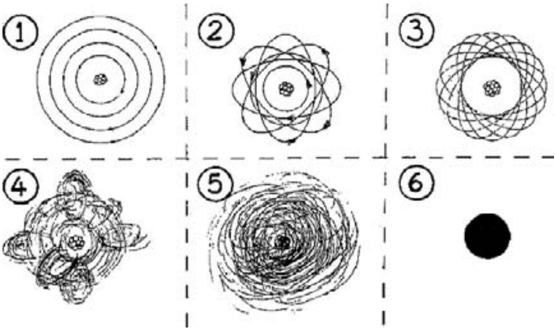


Fig. 3.4 The set of six diagrams of atomic models presented to students (p. 516)

students were asked to draw what they perceived to be an atom and were asked to choose two from six diagrammatic representations of an atom which were closest to their perception (as in Fig. 3.4). Except option (6), all others could represent the verbal description that the atomic nucleus is surrounded by electrons. Although the drawings produced by the students are not available in the cited paper, the options chosen by them are revealing. The majority of students preferred (2) and indicated they disliked (4). That is, they tended to appreciate a distinct and concrete atomic model. From the report, it is unclear how many participants of study have been introduced the notion 'electron cloud' and quantum mechanical model of atomic structure. Nevertheless, students' preference could inform teachers about students' prior conception when they start to learn more advanced atomic model in which electrons do not follow definite orbits. Teachers would thus be aware of the need to highlight the differences between different representations of atomic models.

It has been suggested that the notion of 'electron cloud' could be more fully explored with the use of the visual mode. There is some evidence that students' understanding of 'cloud' is alternative to the accepted scientific view. In a study which investigated students knowledge of the water cycle, it was found that some of the children age 5–15 viewed 'clouds' as sponges in which drops of water are embedded (Bar, 1989). If students are not able to grapple with the scientific meaning embedded in 'cloud', then it would be much more difficult to grasp their understanding of the verbal analogy between 'electron cloud', meaning an 'electronic arrangement', and 'cloud'. If students were presented with a diagram showing an electron cloud, and then probed explicitly as to where the electrons are and the relationship to the idea of 'cloud', then we could be far more sure that we understood their meaning.

Textbook Photographs and Diagrams

Diagrams and photographs prevail in science texts from primary school level to professional publications. From an analysis of biology texts, it was proposed that textbook photographs take four forms and serve four functions: (i) decorative – photographs without captions or references in the text (ii) illustrative – photographs with the names of the objects/phenomena only in the caption (iii) explanatory – photographs with the names and some explanations/classifications of the phenomena in the caption and (iv) complementary functions – photographs showing new information not available/mentioned in the main text (Pozzer & Roth, 2003). The report suggests that if photographs serve only decorative or illustrative functions, they might not be necessary. Nevertheless, taking the multimodal perspective of learning and teaching, the visual mode of representation produces a meaning that is different from that of the verbal mode. It is through their interactions that meanings are constructed. In that sense, 'decorative' and 'illustrative' could also provide significant information that would otherwise be impossible to carry in words. For example, an illustration of an animal species or physical phenomena that students have not seen before would be conducive to their meaning-making from the combination of text and image.

More recently, Pozzer-Ardenghi and Roth (2005) have reported how secondary school students could understand textbook photographs. The study presented photographs, with and without caption and accompanying text, to students. Not surprisingly, it was found that photographs alone did not ensure successful comprehension by the students. For example, students were not able to discern what can be regarded as salient elements in the photographs. Also, identifying patterns from a series of photographs could not be guaranteed without the aid of captions and/or associated texts. In short, the role of caption and texts is essential in guiding students how to make meanings from photograph(s). The findings and implications of the study are relevant to the multimodal view of learning, i.e. each individual mode of representation contributes to part of the union meaning of a concept. It was the co-deployment of the visual and the verbal mode that enables students to make sense of the meanings intended by textbook authors.

By the same token, the inclusion of diagrams could negatively affect students' interpretation. Crisp and Sweiry (2006) studied students' performance in examination questions. They found that on some occasions the inclusion of a diagram supplemented the verbal information provided in the examination questions whilst on other occasions the use of different diagrams associated with the same verbal questions did not significantly affect students' performance. However, when students were provided with Fig. 3.5 and asked for the products of the reaction between hydrochloric acid and sodium carbonate, which is an ingredient of toothpaste, 9% of students gave answers such as 'shampoo' and 'soap'.

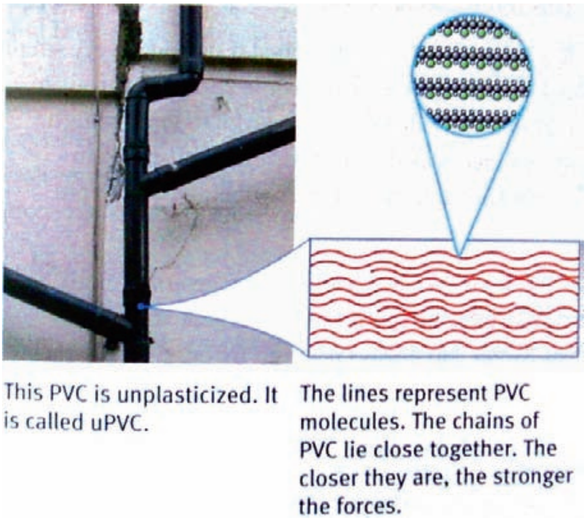
The authors postulate that it is the word 'products' in the question that triggers students to name the household products that they see from the photograph. In this case, although the photograph aims to illustrate toothpaste, it turns out that students inappropriately associate the other elements in the photographs with the verbal information provided in the question.

With the studies conducted so far, what is not clear is how exactly different modes of representations have contributed to the meaning construction. That is, what are the specific affordances of visual and verbal modes utilized in textbook? Further studies seem to be needed to answer this question if more effective instructional materials are to be designed to enhance students' learning.

Fig. 3.5 The diagram associated with an examination question – what are the products of the reaction between hydrochloric acid and sodium carbonate which is an ingredient of toothpaste (Crisp & Sweiry (2006)

Implication for Chemistry Education

Diagrams and photographs are prevalent in chemistry textbooks. Given that students are required to translate between the macroscopic, microscopic and symbolic levels of understanding and be able to visualize a 3D structure from a 2D representation, the visual mode of representation plays a special role in meaning-making process (Gilbert, 2008). Particularly, how do students interpret figure, such as the one in Fig. 3.6, which attempts to illustrate the macroscopic and microscopic level of the physical world? As exemplified in the representations of the ionization of HF, it is inevitable that the information represented in the verbal mode and the visual mode do contradict each other, how well do students reconcile the inconsistencies when they read the textbooks? Also, it has been found that school students might assign



This PVC is unplasticized. It is called uPVC.

The lines represent PVC molecules. The chains of PVC lie close together. The closer they are, the stronger the forces.

Fig. 3.6 A diagram linking macroscopic and microscopic levels. [Source: *21st Century Science: Chemistry*, (Hunt & Grayson, 2006, p. 51)] different values for learning to visual aids, in the order of cartoons, pictorial diagrams, diagrams (with labels and process arrows) and abstract line drawings (Newberry, 2002). In this connection, how do students perceive the value of photographs, or a figure which comprise a mix of photographs and diagrams (Fig. 3.6)? At a more metacognitive level, how do students perceive the nature of the visual mode of representation? How do they understand diagrams/ photographs as visual model of physical phenomena? What would be the different levels of representational competence? These are all pertinent questions related to how students make sense of visual mode of representation when learning chemistry.

In this connection, the ‘visual grammar’ framework proposed by Kress and van Leeuwen (2006) would be a useful tool for the analysis of the contents of diagrams. The ‘visual grammar’ has made significant reference to work on ‘functional grammar’ by Halliday (1985). In essence, like a linguistic system, the resources of visual system, i.e. images, serve the following three metafunctions simultaneously:

- Ideational/Representational meaning: The image represents aspects of the world experienced, perceived or conceptualized by humans. Examples of such aspects include events, objects and ideas *etc*.
- Interpersonal/ Interactive meaning: The image constructs the nature of relationship between the viewer and the objects represented within the image.
- Textual/Compositional meaning: The image constructs meaning through the spatial distribution and the relative emphasis of different elements within it.

As the interest of this chapter is about how diagrams represent the world external to them and how readers could make sense of them, we will focus on the ideational/ representation meanings made by diagrams. Based on the framework of ‘visual grammar’, in the context of school chemistry, a diagram can represent, in the opinion of Kress and van Leeuwen (2006), one or more of the following processes:

1. *Action process* – a representation of an unfolding action and event processes of change and transitory spatial arrangement (e.g. a diagram showing how a sodium atom becomes a sodium atom through the loss of the outermost shell electron).
2. *Conversion process* – a chain of process in a cycle (e.g. carbon cycle or other material cycles).
3. *Classification process* – such as a tree diagram that shows how different things can be categorized from the most general to the most specific terms.
4. *Analytical process* – a representation of how a ‘whole’ is made of ‘parts’. When the ‘whole’ is made of a series of key events, it is called *temporal analytic process* (e.g. a series of diagram showing the key steps of a practical work). When the ‘whole’ is made of its ‘parts’ arranged in a spatial relationship, it is called *spatial analytic process* (e.g. a diagram showing the arrangement of carbon atoms in a piece of graphite/ diamond).

Therefore, it would be worthwhile to investigate how students understand the diagrammatic representation of these processes as they encounter them in textbooks and in classroom teaching.

Diagrams and photographs play a substantial role in the learning of chemistry (Gilbert, 2006). Usually, this role has been discharged through the use of illustrations at the beginning of a chapter/ topic area. Stylianidou et al. (2002) have investigated how students interpret an illustration at the outset of their study of the topic ‘Energy’. It was found that many students were not able to identify issues related to the topic. In another words, the illustration, although vivid, failed to set the context for students. Thus, it would be useful if we are able to develop criteria for the design /selection of illustrations that can help in setting the context for students learning. In terms of teaching, how can teachers help students to gain detailed access to a particular context for learning? What is successful and what is not? These issues could be more fully explored in further investigation.

Students’ Understanding Probed Through Produced Diagrams

‘Sea’ of Electrons and Metallic Bonding

Taber (2002) demonstrated how student’ drawings have acted as a window through which a researcher can understand learners’ *internal representation* of metallic bonding which is otherwise not accessible via words or textual data. For example, through the drawings in Fig. 3.7, we could learn what a ‘sea of electrons’ could mean to students – i.e. ‘a *vast excess* of electrons which would not be possible in a neutral metal structure’ (p. 744). Like many other scientific ideas, there could have been many different interpretations based only on a verbal description. It is only with the inclusion of visual mode that the notion of a ‘sea of electrons’ is qualified. From students’ drawings, it could be suggested that they have inappropriately translated the meaning of ‘sea of electrons’ as something overwhelmingly bathing the metallic ions. Again, it is an indication of inappropriate association of visual and verbal mode of representation.

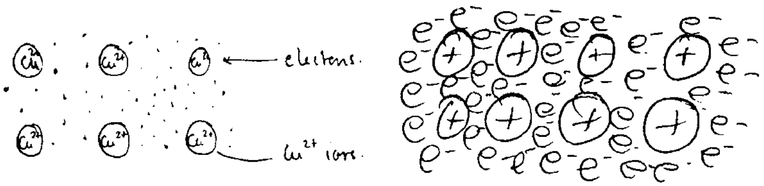


Fig. 3.7 Students’ external representations of metallic lattice at microscopic level and sea of electron (Taber, 2002, pp. 745–746)

Further Possibilities for Analysis

If the potentials of diagrams are to be fully exploited, it would be revealing to ask students to compare what they have drawn with a corresponding illustration depicted in their textbooks. Based on the idea that people visualize things with the support of their own knowledge of the world, we suspect that some students may not be able to point out the differences between their own diagram and a textbook illustration. If this is the case, we will have to re-consider how students would construe meaning through textbook diagrams (see for example, Stylianidou et al. (2002) and Ametller and Pintó (2002) which demonstrated a similar line of enquiry).

Representation of Chemical Reactions

The drawings produced by students allow researchers to better conceptualize how some students interpreted a balanced chemical equations. This is especially useful in assessing their understanding of stoichiometric coefficients and the meaning of subscripts of chemical formulae.

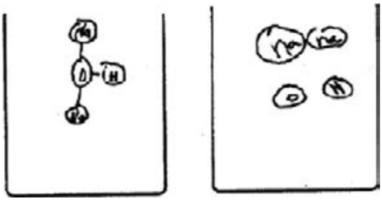
Learning various kinds of chemical reactions and physical processes is an important element of all chemistry curricula. Earlier in this chapter we commented on how students could recite the verbal definition of a strong acid but yet failed to select a visual representation that best illustrates the complete ionization of hydrogen chloride molecules. Another part of this study, conducted by Smith and Metz (1996), was probing students' microscopic representation of the reaction

$$\mathrm{NiCl_2\ (aq) + 2NaOH\ (aq) \rightarrow Ni(OH)_2\ (s) + 2NaCl\ (aq)}$$

For example, it was found that some students interpreted 2NaOH as meaning that two sodium atoms were linked together (Fig. 3.8); similarly $NiCl_2$ is regarded as separate units of Ni and Cl_2 (Fig. 3.9). That is, they might have seen stoichiometric coefficient and subscripts of chemical formulae as bearing the same information. A very similar finding was reported using the reaction $N_2 + 3H_2 \rightarrow 2NH_3$ (Yorroch, 1985). Although all students participated in the study were able to balance the equation, upon further probing through drawing and interview, some of the students fail to discern the meanings of subscripts and stoichiometric coefficient, and perhaps the meaning embedded in chemical formula NH_3 (Fig. 3.10).

Although not commented on by Smith and Metz (1996), the drawings in Figs. 3.8 and 3.9 might have revealed that some of the students were not entirely familiar with the state symbols. The question and the equation stated explicitly that the reaction takes place in aqueous solution. Nevertheless, these drawings did not make any reference to the fact that the reaction or the chemical species are in an aqueous medium.

Fig. 3.8 Drawings produced by different students about their mental picture of '2NaOH' (p. 235)



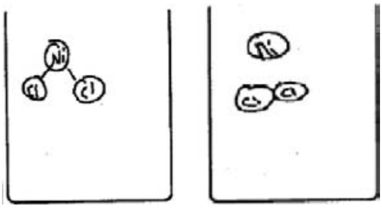


Fig. 3.9 Drawings produced by different students about their mental picture of '$NiCl_2$' (p. 235)

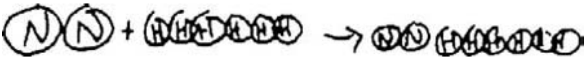


Fig. 3.10 Students' representation of $N_2 + 3H_2 \rightarrow 2NH_3$

Also, it seems that some students failed to identify the notation for covalent bonding, i.e. a short horizontal line, to denote the attractive forces between ions (see the left pictures of Figs. 3.8 and 3.9). This is also evident in a diagram in which the above authors have judged to have met all the important criteria of a good representation of the chemical reaction (Fig. 3.11). Therefore, other than the meaning embedded in stoichiometric coefficients and subscripts, it would be meaningful to probe students' understanding of the state symbols and the kind of interactions between different chemical species in a chemical reaction based on their own drawings.

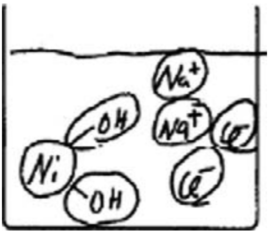


Fig. 3.11 Nickel ion and hydroxide ions linked by two strokes (p. 234)

Concept Mapping

The use of concept mapping in science education was introduced more than two decades ago (Novak & Gowin, 1984). Extensive research studies have been conducted to investigate how it can be used to enhance teaching, learning and the validity of assessment. It is found that almost all of the research reports have either used student- constructed concept maps (Kinchin & Hay, 2000) or constructed a concept map from interviews with informants as the source of data for analysis (Nicoll, Francisco, & Nakhleh, 2001). In general, there is a consensus that concept maps do enhance meaningful and deep learning among students. Also, student-constructed concept maps have been shown to be an effective tool in representing their understanding of content knowledge in and across different topics.

If a concept map is regarded as a representation of knowledge and that a set of given concepts can be linked meaningfully but differently, it is surprising that how students make meaning from a given concept map has not been extensively studied.

Although it is generally believed that it would be more meaningful if students were to construct their own concept maps, in view of the fact that it is more common for the new editions of textbooks at school and college level to include concept maps in their texts, it would be worthwhile to investigate what students could interpret and make sense of this form of visual representation. Based on the work of Pozzer-Ardenghi and Roth (2005) who probed students interpretation of photographs with and without captions and associated text, similar studies can be conducted with the use of concept maps in place of photographs.

Alternatively, in order to better understand students' mental model of particular content area(s), students can be presented with two concept maps which are constructed with the same concept labels and then probed for their interpretation and comparison of the two representations. This approach would help us to understand which organization of concepts students find easier to grapple with and the difficulties they face with respect to certain linkages of concepts.

Probing Students' Conceptions

Research studies utilizing students' drawings have not only probed their content knowledge but also their attitudes to and conceptions of science. One line of enquiry has involved students' drawings of their conceptions of 'environment' (Alerby, 2000; Shepardson, Wee, Priddy, & Harbor, 2007; Wee, 2007). These studies have demonstrated that children of different age/grade, sex and in different parts of the world do perceive 'environment' differently. For example, although students from Singapore and the U.S. hold a utilitarian worldview where the environment provides materials such as sunlight, water and oxygen for human existence, those from the U.S. tend to see environment as a place where plants and animals live. In contrast, students from Singapore, a geographically small, highly urbanized, country where everything is very neat and clean, are more likely to include human impacts such as buildings and litter bins in their drawings (Wee, 2007). A study conducted in Sweden (Alerby, 2000) demonstrated that, while younger students tend to perceive 'environment' as clean and unspoilt nature (the good world), those from an older age group tend to conceptualize both the 'good' and the 'bad' (dirty, polluted) world. Also, compared with boys, girls are more likely to focus on the 'good' world. Alerby (2000) also proposes that the participants in general held an anthropocentric view about the world, which is a fundamental component in the Judeo-Christian traditions. However, drawings produced by Singaporean students also reveal similar values, suggesting that this view is shared more world-wide and prevalent beyond the strong influence of the Judeo-Christian tradition.

Although the above discussion might not directly map onto chemical education, we would like to propose that studies of similar nature could be conducted which probe students' conceptions of issues related to chemistry. For example, such studies could be about 'the impact of chemistry on humankind', 'risks and benefits of using plastics/ metals' or, in a broadest sense, 'the chemical world'. These drawings could not only allow students to express their ideas which cannot be replaced by verbal mode of communication, but also allow researchers or teachers to see students' conceptions and attitudes towards issues related to chemistry. It would be revealing to see, like 'drawing-the-environment', whether students hold a positive, a negative or a more neutral attitude towards the discipline and its impact on the Earth and human race.

The Validity of Drawn Diagrams in Representing Internal Representations

A typical example that utilizes students drawing is the drawing-a-scientist exercise (sometimes called the draw-a-scientist test, DAST). Usually, students are asked to draw their perceived image of a scientist. Repeated studies conducted in different parts of the world over the past few decades have demonstrated that students hold stereotypical images of scientists – i.e. white male, wearing lab coat, holding test tubes and with wild and weird hairdos, etc. The reliability of drawing *a* scientist has been questioned by Farland and McComas (2007) who asked students to produce three pictures of scientists at work. This approach aimed at allowing students to represent their ideas on more than one occasion, hence probing into students' possible multiple images of scientists. Their data shown that in only 24% of cases (N=106) were the first drawings indicative of the other two. This shows that simply asking students to draw one scientist has not been a reliable way of probing students' images of scientists. Instead of holding a single stereotypical image of scientists, it is very likely that students can hold very different images. This can be supported by a drawing made by a 13-year-old boy about his conception of 'environment' (Alerby, 2000; Fig. 3.12). In his drawing, he has already drawn two completely opposite diagrams about his conceptions of environment without probing.

The implication of the study by Farland and McComas (2007) is that more than just the significance of the multimodal representation of ones' ideas. It is also about

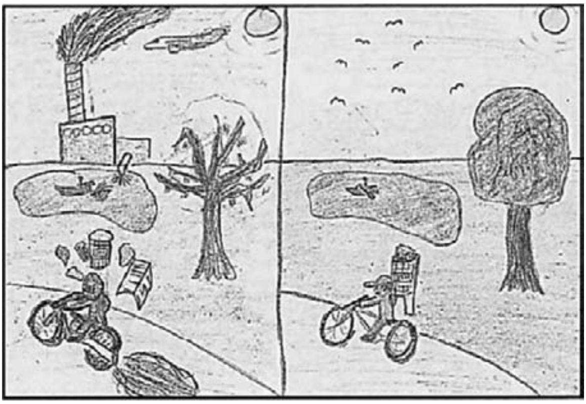


Fig. 3.12 'I'm thinking of a bad and a good environment' (boy, 13 years old) (Alerby, 2000, p. 215)

what could enhance the reliability of drawing produced by students. This finding is relevant not only in revealing students' attitudinal aspect about science, but could be extended to their representation of content knowledge and understanding.

Conclusion

This chapter has called for a better utilization of diagrams in chemical educational research generally and especially into the macro/sub-micro/symbolic representational triplet.

Research into the use of diagrams would enable their use as ways of promoting both the development of and assessment of meta-visual capability to be explored. Such research might

- establish the interpretational conventions used in diagrams. It is possible that several fundamental genres of diagrams exist, with hybrids of these being widely used. With these conventions identified, it would be possible to systematically teach their use in the sub-micro level of representation and hence their relationship to allied macro and symbolic level representations.
- establish the mental processes involved in mental translation between diagrams and other forms of representation. These could then be taught.
- establish heuristics for the construction of diagrams for different purposes. Again, these could be taught.

The arguments made can readily be extended to research into education in respect of the other sciences. We started by highlighting the multimodal approach of learning and teaching science. This perspective emphasizes the roles of different modes of representation in making meaning. We suggested that most of the research into students' understanding of science has made too much use of only the verbal mode of representation of knowledge. This has left the visual mode of representation under-explored. In order to identify some directions for further investigation, we have conducted an indicative literature review about how to utilize diagrams to probe into students' understanding. The studies were divided into two categories which include those which probed students' understanding through their own drawings and those eliciting students' interpretation of diagrams presented to them. We found many of these studies have focused on students' understanding of fundamental chemistry concepts, such as atomic theory, particulate model of matter, chemical bonding, chemical reactions and equations. From these studies, we identified some possibilities for future work, such as a more detailed probe of the meanings of notations and conventions in drawings, asking students to compare their own drawings from the textbooks diagrams, and inviting students to draw/interpret diagrams of some abstract concepts or the concepts which were found to easily incur alternative conceptions (e.g. electron clouds). What is emerging is that probing students' attitudes and conceptions about science through drawing has great potential for chemical education to exploit. Similarly, how students could make meanings from the diagrams, cartoons and photographs of chemistry textbooks, especially how students construct meanings from the visual and verbal mode of representation together, which sometimes are contradictory, can be explored. At a metacognitive level, we suggest that how students understand the role of 'visuals as scientific models' can be studied.

Acknowledgments An earlier version of this paper was presented at the European Science Education Research Association conference held in Malmo, Sweden, August 2007

References

Alerby, E. (2000). A way of visualizing children's and young people's thoughts about the environment: A study of drawings. *Environmental Education Research, 6*(3), 205–222.

Ametller, J., & Pintó, R. (2002). Students' reading of innovative images of energy at secondary school level. *International Journal of Science Education, 24*(3), 285–312.

Bar, V. (1989). Children's views about the water cycle. *Science Education, 73*(4), 481–500.

Crisp, V., & Sweiry, E. (2006). Can a picture ruin a thousand words? The effects of visual resources in exam questions. *Educational Research, 48*(2), 139–154.

Farland, D. L., & McComas, W. F. (2007, 15–18 April). *The enhanced (E-DAST): A more valid, efficient, reliable and complete method of identifying students' perceptions of scientists.* Paper presented at the National Association of Research in Science Teaching (NARST), New Orleans, USA.

Fensham, P. J. (2001). Science content as problematic – issues for research. In H. Behrendt, H. Dahncke, R. Duit, W. Gräber, M. Komorek, A. Kross, & P. Reiska (Eds.), *Research in science education – Past, present, and future* (pp. 27–41). Dordrecht, Boston, MA: Kluwer Academic Publishers.

Gabel, D. (1998). The complexity of chemistry and implications for teaching. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education*. Dordrecht, Netherlands: Kluwer Academic Publishers.

Garnett, P. J., Garnett, P. J., & Treagust, D. (1990). Implication of research on students' understanding of electrochemistry for improving science curricula and classroom practice. *International Journal of Science Education, 12*(1), 147–156.

Gilbert, J. K. (2006). On the nature of 'context' in chemical education. *International Journal of Science Education, 28*(9), 957–976.

Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education,* pp. 3–24. Dordrecht: Springer.

Halliday, M. A. K. (1985). *An introduction to functional grammar*. London: Edward Arnold.

Harrison, A. G., & Treagust, D. F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education, 80*(5), 509–534.

Hunt, A., & Grayson, A. (2006). *Twenty first century science: GCSE chemistry*. Oxford: Oxford University Press.

Kinchin, I. M., & Hay, D. B. (2000). How a qualitative approach to concept map analysis can be used to aid learning by illustrating patterns of conceptual development. *Educational Research, 42*(1), 43–57.

Kress, G., Jewitt, C., Ogborn, J., & Tsatsarelis, C. (2001). *Multimodal teaching and learning: The Rheotorics of the science classroom*. London, New York: Continuum.

Kress, G., & van Leeuwen, T. (2006). *Reading images: The grammar of visual design* (2nd ed.). London, New York: Routledge.

Lemke, J. (1998). Multiplying meanings: Visual and verbal semiotics in scientific text. In J. R. Martin & R. Veel (Eds.), *Reading science: Critical and functional perspectives on discourse of science* (pp. 87–113). London: Routledge.

Mathewson, J. H. (1999). Visual-spatial thinking: An aspect of science overlooked by educators. *Science Education, 83*(1), 33–54.

Nakhleh, M. B. (1994). Chemical education research in the laboratory environment – how can research uncover what students are learning? *Journal of Chemical Education, 71*(3), 201–205.

Newberry, M. (2002). *Pupils' understanding of diagrams in science: Progression from Key Stage 3 (11–14 years) and across Key Stage 4 (14–16 years)*. Fareham, Hants: Cams Hill Schoolo. (Document Number).

Nicoll, G., Francisco, J., & Nakhleh, M. (2001). An investigation of the value of using concept maps in general chemistry. *Journal of Chemical Education, 78*(8), 1111–1117.

Novak, J. D., & Gowin, D. B. (1984). *Learning how to learn*. Cambridge, UK: Cambridge University Press.

Novick, S., & Nussbaum, J. (1978). Junior high school pupils' understanding of the particulate nature of matter: An interview study. *Science Education, 62*(3), 273–281.

Nurrenbem, S. C., & Pickering, M. (1987). Conceptual learning versus problem solving: is there a difference? *Journal of Chemical Education, 64*(6), 508–510.

Pozzer-Ardenghi, L., & Roth, W.-M. (2005). Making sense of photographs. *Science Education, 89*(2), 219–241.

Pozzer, L. L., & Roth, W.-M. (2003). Prevalence, function, and structure of photographs in high school biology textbooks. *Journal of Research in Science Teaching, 40*(10), 1089–1114.

Reiss, M. J., & Tunnicliffe, S. D. (2001). Students' understandings of human organs and organ systems. *Research in Science Education, 31*(3), 383–399.

Shepardson, D. P., Wee, B., Priddy, M., & Harbor, J. (2007). Students' mental models of the environment. *Journal of Research in Science Teaching, 44*(2), 327–348.

Smith, K. J., & Metz, P. A. (1996). Evaluating student understanding of solution chemistry through microscopic representations. *Journal of Chemical Education, 73*(3), 233–235.

Stark, J. G., & Wallace, H. G. (Eds.). (1982). *Chemistry data book* (2nd ed.). London: John Murray.

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction, 17*, 219–234.

Stylianidou, F., Ormerod, F., & Ogborn, J. (2002). Analysis of science textbook pictures about energy and pupils' reading of them. *International Journal of Science Education, 24*(3), 257–283.

Taber, K. S. (2002). Mediating mental models of metals: Acknowledging the priority of the learner's prior learning. *Science Education, 87*(5), 732–758.

Tuckey, H., & Selvaratnam, M. (1993). Studies involving three-dimensional visualisation skills in chemistry: A review. *Studies in Science Education, 21*, 99–121.

Viennot, L., & Kaminski, W. (2006). Can we evaluate the impact of a critical detail? The role of a type of diagram in understanding optical imaging. *International Journal of Science Education, 28*(15), 1867–1885.

Wee, B. (2007, 15–18 April). *An international comparison of children's drawings: conceptions of the environment in Singapore and the United States.* Paper presented at the National Association of Research in Science Teaching (NARST), New Orleans, USA.

Yorroch, W. L. (1985). Student understanding of chemical equation balancing. *Journal of Research in Science Teaching, 22*(5), 449–459.

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

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_5,

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 (*re-cognising*) 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)

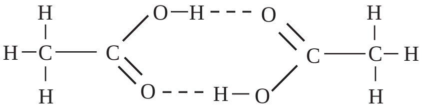


Fig. 4.1 A complex pattern or a simple representation?

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

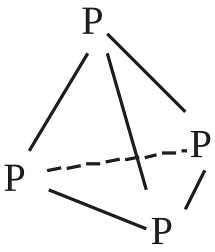


Fig. 4.2 A representation of a P_4 molecule

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 ($^3P_1$, $^1S_0$, $^3A_{2g}$, $^3T_{1g}$, $e_g^1t_{2g}^1$, $^3T_{2g}$). 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.

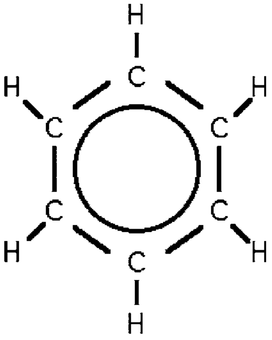
Symbols Used to Represent Structure and Process in Organic Chemistry

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 →]
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	$6CO_2 + 6H_2O\ {}^{h\nu} \rightarrow C_6H_{12}O_6 + 6O_2$ [$h\nu$ should be above →]
8	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + energy
9	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \Delta H = -\ 890\ \text{kJ mol}^{-1}$
10	$Na \rightarrow Na^+ + e^- \qquad \Delta H = 500\ \text{kJ mol}^{-1}$
11	$MnO_4{}^- + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O \qquad E^{\emptyset} = +1.52\ V$ [$^{\emptyset}$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 (↑) and precipitates formed (↓). Other key symbols indicate reactions (→), equilibria (⇔,), conditions for reactions such as heat (Δ) and light ($h\nu$, 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:

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

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):

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

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:

$$\begin{gathered}
\mathrm{2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O} \\
\mathrm{NaOH + NaOH + H_2SO_4 \rightarrow Na_2SO_4 + H_2O + H_2O} \\
\mathrm{Na + O + H + Na + O + H + H + H + S + O + O + O + O =} \\
\mathrm{Na + Na + S + O + O + O + O + H + H + O + H + H + O} \\
\mathrm{Na + Na + O + O + O + O + O + O + H + H + H + H + S =} \\
\mathrm{Na + Na + S + H + H + H + H + O + O + O + O + O + O} \\
\mathrm{2Na + 6O + 4H + S = 2Na + S + 4H + 6O}
\end{gathered}$$

whereas

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

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,

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

where state symbols indicate the states of the reactants, it may seem superfluous indicating the water produced. If we wrote this equation as

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

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:

$$\begin{gathered} MnO_4^- + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O \\ (-1) + 8(1+) + 5(-1) = (+2) + 4(0) \\ -1 + 8 - 5 = +2 \end{gathered}$$

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:

$$\mathrm{Ag}^{+}_{(aq)} + \mathrm{NO}_{3\ (aq)}^{-} + \mathrm{Na}^{+}_{(aq)} + \mathrm{Cl}^{-}_{(aq)} \rightarrow \mathrm{AgCl}_{(aq)} \downarrow + \mathrm{Na}^{+}_{(aq)} + \mathrm{NO}_{3\ (aq)}^{-}$$

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:

$$\mathrm{Ag}^{+}{}_{(aq)} + \mathrm{Cl}^{-}{}_{(aq)} \rightarrow \mathrm{AgCl}_{(aq)} \downarrow$$

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:

$$\mathrm{Na} \rightarrow \mathrm{Na}^{+} + \mathrm{e}^{-}$$

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 ($\Leftrightarrow$, $\rightleftharpoons$) 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 ⇔) and reversible (signified →) 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 ^{2}H becomes substituted by ^{2}D 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 → symbol has a different meaning to the ⇔ 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 ‘→’ (open arrow head) should mean something different to ‘→’ (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:

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

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.

$$\text{glucose} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

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?

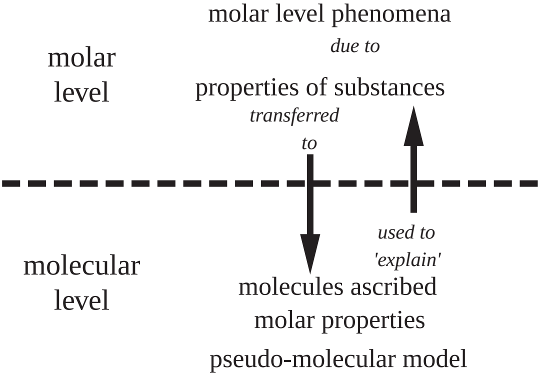


Fig. 4.4 How learners misapply particle models (from Taber, 2000b; previously published in Taber, 2001b)

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,

$$\mathrm{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$$

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.

References

Ahtee, M., & Varjola, I. (1998). Students' understanding of chemical reaction. *International Journal of Science Education, 20*(3), 305–316.

Ausubel, D. P. (2000). *The acquisition and retention of knowledge: A cognitive view* (pp. 85–99). Abingdon, Oxon: Routledge.

Baddeley, A. (1990). *Human memory: Theory and practice*. Hove, East Sussex: Lawrence Erlbaum Associates.

Bannerjee, A. C. (1991). Misconceptions of students and teachers in chemical equilibrium. *International Journal of Science Education, 13*(4), 487–494.

Ben-Zvi, R., Eylon, B-S., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*(1), 64–66.

Capra, F. (1983). *The Tao of physics: An exploration of the parallels between modern physics and Eastern mysticism* (Rev. ed.). London: Fontana.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. N. Giere (Ed.), *Cognitive models in science* (pp. 129–186). Minneapolis: University of Minnesota Press.

Chittleborough, G. D., Treagust, D. F., & Mocerino, M. (2002, February 2002). Constraints to the development of first year university chemistry students' mental models of chemical phenomena. Presented at the 11th Annual Teaching and Learning Forum for Western Australian Universities, Edith Cowan University, Australia.

Cokelez, A., Dumon, A., & Taber, K. S. (2007). Upper secondary french students, chemical transformations and the "Register of Models": A cross-sectional study [Electronic version]. *International Journal of Science Education*, 1–30, DOI: 10.1080/09500690701308458.

Davidson, G. (1971). *Introductory group theory for chemists*. London: Applied Science Publishers.

DfES (2003). *Strengthening teaching and learning of energy in Key Stage 3 science*. London: Key Stage 3 National Strategy, Department for Education and Skills.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*. Buckingham: Open University Press.

Driver, R., & Millar, R. (1986). *Energy matters*. Leeds, U.K.: Centre for Studies in Science and Mathematics Education.

Feynman, R. (1967). *The character of physical law*. Cambridge, MA: MIT Press.

Gilbert, J. K. (2005). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert, (Ed.) *Visualization in science education* (pp. 9–27). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Gilbert, J. K., Taber, K. S., & Watts, M. (2001). Quality, level, and acceptability, of explanation in chemical education. In A. F. Cachapuz (Ed.), *A chemical odyssey*. Proceedings of the 6th European Conference in Research in Chemical Education/2nd European Conference on Chemical Education, University de Aveiro, Portugal.

Gregory, R. L. (1997). Knowledge in perception and illusion. *Philosophical Transactions of the Royal Society B (Biological Sciences), 352*(1358), 1121–1128.

Grevatt, A., Gilbert, J. K., & Newberry, M. (2007). Challenging able science learners through models and modelling. In K. S. Taber (Ed.), *Science education for gifted learners* (pp. 85–99). London: Routledge.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*(9), 799–822.

Harrison, A. G., & Treagust, D. F. (2002). The particulate nature of matter: challenges in understanding the sub-microscopic world. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, & J. H. van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 189–212). Dordecht: Kluwer Academic Publishers.

Jensen, W. B. (1998). Logic, history, and the chemistry textbook: I. Does chemistry have a logical structure? *Journal of Chemical Education, 75*(6), 679–687.

Jensen, W. B. (2005). The origins of the symbols A and Z for atomic weight and number. *Journal of Chemical Education, 82*(12), 1764.

Jensen, W. B. (2006). The use of dots in chemical formulas. *Journal of Chemical Education, 83*(11), 1590–1591.

Johnson, P. (2002). Children's understanding of substances, Part 2: explaining chemical change. *International Journal of Science Education, 24*(10), 1037–1054.

Johnstone, A. H. (2000). Teaching of Chemistry – logical or psychological? *Chemistry Education: Research and Practice in Europe, 1*(1), 9–15.

Ladhams Zieba, M. (2004). *Teaching and Learning about Reaction Mechanisms in Organic Chemistry*. PhD thesis, University of Western Australia, Australia.

Laidler, K. J. (1981). Symbolism and terminology in chemical kinetics. *Pure and Applied Chemistry, 53*(3), 753–771.

Marais, P., & Jordaan, F. (2000). Are we taking symbolic language for granted? *Journal of Chemical Education, 77*(10), 1355–1357.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences, 7*(7), 293–299.

Miller, G. A. (1968). The magical number seven, plus or minus two: Some limits on our capacity for processing information. In *The psychology of communication: Seven essays* (pp. 21–50). Harmondsworth: Penguin.

Nemeroff, C., & Rozin P. (2000). The makings of the magical mind: the nature and function of sympathetic magical thinking. In K. S. Rosengren, C. R. Johnson, & P. L. Harris (Eds.), *Imagining the impossible: Magical, scientific and religious thinking in children* (pp. 1–34). Cambridge: Cambridge University Press.

Nelson, P. G. (2002). Teaching chemistry progressively: From substances, to atoms and molecules, to electrons and nuclei. *Chemistry Education: Research and Practice in Europe, 3* (2), 215–228. Retrieved 22nd November, 2007, from http://www.uoi.gr/cerp/2002_May/11.html.

Pinker, S. (1995). *The language instinct*. London: Penguin.

Pope, M., & Watts, M. (1988). Constructivist goggles: Implications for process in teaching and learning physics. *European Journal of Physics, 9*, 101–109.

Sanders, M. (1993). Erroneous ideas about respiration: The teacher factor. *Journal of Research in Science Teaching, 30*(8), 919–934.

Schmidt, H-J. (1991). A label as a hidden persuader: chemists' neutralization concept. *International Journal of Science Education, 13*(4), 459–471.

Sliwka, H-R. (2003). Reform of chemical language as a model for spelling reform [Electronic version]. *Journal of the Simplified Spelling Society, 32*, 24–28. Retrieved August 6, 2007, from http://www.spellingsociety.org/journals/j32/chemical.php.

Solomon, J. (1992). *Getting to Know about energy – in school and society*. London: Falmer Press.

Taber, K. S. (1994, 10th September). Can Kelly's triads be used to elicit aspects of chemistry students' conceptual frameworks?. Paper presented at the British Educational Research Association Annual Conference. The text is available from the Education-line internet document collection at: http://www.leeds.ac.uk/educol.

Taber, K. S. (1998). An alternative conceptual framework from chemistry education. *International Journal of Science Education, 20*(5), 597–608.

Taber, K. S. (2000a). Chemistry lessons for universities? A review of constructivist ideas. *University Chemistry Education, 4*(2), 26–35. Available at http://www.rsc.org/Education/CERP/issues/

Taber, K. S. (2000b, 5th September). *Molar and molecular conceptions of research into learning chemistry: towards a synthesis*. Lecture given at the variety in chemistry teaching meeting at the University of Lancaster. Retrieved November 22, 2007, from http://www.rsc.org/Membership/Networking/InterestGroups/ChemicalEducationResearch/Lectures.asp

Taber, K. S. (2001a). The mismatch between assumed prior knowledge and the learner's conceptions: a typology of learning impediments. *Educational Studies, 27*(2), 159–171.

Taber, K. S. (2001b). Building the structural concepts of chemistry: Some considerations from educational research. *Chemistry Education: Research and Practice in Europe, 2*(2), 123–158. Retrieved November 22, 2007, from http://www.uoi.gr/cerp/2001_May/09.html.

Taber, K. S. (2002a). *Chemical misconceptions – prevention, diagnosis and cure*, 2 vols. London: Royal Society of Chemistry.

Taber, K. S. (2002b). Compounding quanta – probing the frontiers of student understanding of molecular orbitals. *Chemistry Education: Research and Practice in Europe, 3*(2), 59–173. Retrieved 22nd November, 2007, from http://www.uoi.gr/cerp/2002_May/07.html

Taber, K. S. (2003a). The atom in the chemistry curriculum: fundamental concept, teaching model or epistemological obstacle? *Foundations of Chemistry, 5*(1), 43–84.

Taber, K. S. (2003b). Understanding ionisation energy: physical, chemical and alternative conceptions. *Chemistry Education: Research and Practice, 4*(2), 149–169. Retrieved November 22, 2007, from http://www.uoi.gr/cerp/2003_May/05.html

Taber, K. S. (2005). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education, 89*(1), 94–116.

Taber, K. S. (2006). Beyond constructivism: The progressive research programme into learning science. *Studies in Science Education, 42*, 125–184.

Taber, K. S. (2007). Conceptual resources for learning science: issues of transience and grain-size in cognition and cognitive structure. [Electronic version] *International Journal of Science Education*, 1–27, DOI: 10.1080/09500690701485082.

Taber, K. S. & Bricheno, P. (2004). Student understanding of chemical equations. University of Cambridge, Faculty of Education. Retrieved November 22, 2007, from www.educ.cam.ac.uk/research/projects/03_06taber.doc.

Tsaparlis, G. (1994). Blocking mechanisms in problem solving from the Pascual-Leone's M-space perspective. In H-J Schmidt (Ed.), *Problem solving and misconceptions in chemistry and physics* (pp. 211–226). Dortmund: International Council of Association for Science Education.

Watts, M. (1983). Some alternative views of energy. *Physics Education, 18*, 213–217.

Wikipedia. (2007). Horizontal and vertical writing in East Asian scripts. Retrieved November 22, 2007, from http://en.wikipedia.org/wiki/Horizontal_and_vertical_writing_in_East_Asian_scripts.

Part II
Improving Existing Pedagogy in Respect of the Triplet Relationship

This section discusses the value of laboratory practical work in providing a sound basis for the development of an understanding of the triplet relationship. Whilst the first three chapters deal with the macro experience and show how progression to the submicro and symbolic can be facilitated, the last starts from the opposite extreme and shows the value of working from the basis of diagrams.

In Chapter 5, Tsaparlis asserts that sound pedagogical practice in respect of the triplet relationship is through an initial focus on the macro and that laboratory practical work is the best basis for that. He then reviews the wide range of, often conflicting and imprecisely stated, aims that can justify laboratory practical work. The range of types of practical work that can be justified within each of the broad classes of aims is set out and the learning theories that can underpin them are discussed. The case study of the relation between ‘the behaviour of gases’ (macro) and ‘the particulate model of matter’ is set out to illustrate how practical work can link the macro and submicro in student understanding. What emerges is an implicit agreement: yes, practical work can link the macro and submicro, provided that all those involved know what the purpose of the activity is.

The research and development work reported in Chapter 6 is an elegant example of how to address a commonly met problem in practical work. Students too often engage in laboratory work in a superficial, mechanical way that involves just doing the practical activity required without linking macro observations to the underlying submicro and symbolic representations that provide an explanation for what is happening. Taking the case of ‘qualitative inorganic analysis’ (which is notorious for fostering ‘activity without understanding’) the authors developed both a teaching package to foster an understanding of the triplet relationship and a test to show that its aims were achieved.

Chapter 7 is also a case study of the outcomes of a deliberate attempt to facilitate the formation of a better linking of experience of the macro with the associated explanation at the submicro and symbolic. In this case, the detail of the actual successes and failures in the formation of the linkages are given for a series of reaction types. The outcome is a series of general recommendations for teaching if learning across the triplet relationship is to be successful.

Because of their representational flexibility, diagrams can readily facilitate the formation of linkages between events at the macro and their interpretation at the submicro and symbolic. Whilst, as a class, diagrams are normally allocated to the submicro, the possibility of representing either the macro or the submicro or the symbolic, or indeed a mixture of the three, within them makes them especially useful in the promotion of understanding of the triplet relationship. In Chapter 8, Davidowitz and Chittleborough discuss the scope of diagrams and in doing so link their affordances to the exercise of visualization. They illustrate their ideas with two case studies of the use of diagrams in effecting a better understanding of the triplet relationship in students from educationally disadvantaged backgrounds.

Chapter 5
Learning at the Macro Level: The Role of Practical Work

Georgios Tsaparlis

Abstract Contact with concrete examples of substances, their reactions and other properties, through the laboratory and other practical activities, is an integral part of chemical education. In this chapter, attention is paid to alternatives to the expository instruction, which has been criticized for placing little emphasis on thinking. Consideration is given to inquiry and project-based laboratories, problem solving, context-based approaches and student cooperative practical activities. Central to laboratory work is the proper observation of phenomena. Content knowledge is crucial for the proper interpretation of observations. On the other hand, failure by students to notice or record all observations, as well as overloading of working memory are main problems. Methods are discussed for directing students' attention to the important observational stimuli in experiments; demonstrations are particularly helpful in this. Concrete experiences may be a prerequisite for a conceptual understanding of chemistry, but this understanding is eventually provided through the submicroscopic and symbolic levels. Connection of the macro level with the other two levels is an integral but difficult task. Ways to achieve the desired macro to submicro and symbolic transition are given consideration; history of science can be of great value here. The chapter concludes with some future perspectives for practical work.

Introduction

The study of chemistry deals essentially with three main aspects: the macroscopic approach, the representational/symbolic dimension and the submicroscopic level of thinking (Johnstone, 1991, 2007).[1] This chapter considers the role of the macroscopic component, taking also into account the other two levels.

G. Tsaparlis (✉)
University of Ioannina, Ioannina, Greece
e-mail: gtseper@cc.uoi.gr

[1] The submicroscopic level is further distinguished into one studying the properties of isolated molecules (represented at the highest level by quantum chemistry) and one studying the statistical behavior of large assembles of molecules (studied by the methods of statistical thermodynamics) (Ben-Zvi, Silberstein, & Mamlok, 1990).

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_6,

The early introduction in chemistry education of levels other than the macroscopic is assumed responsible for the poor learning of chemistry by young students and for its bad image among them. Tsaparlis (1997) has used various perspectives of science education (Piaget's theory of cognitive development, Ausubels' theory of meaningful learning, the alternative frameworks' perspective and the information processing model) to show that grasping of the abstract structural concepts of chemistry is a very hard task for students. We must stay with the macro level until students have formed new concepts before we attempt to introduce 'explanations' based on submicro considerations (Johnstone, 2007). The introduction of the other two levels must be a gradual process, leading students into the chemists' world.

Johnstone (2007, p. 10) suggested that curriculum designers and textbook writers should consider the need for

> a considerable introductory period in which students get familiar with *thinking in a scientific way through the use of macro and tangible experiences only*. There is plenty of good science to be learned without the 'interference' of sub-micro considerations. Chemistry as a macro material science, dealing with the things of every day experience, has much to offer.

Such an approach is consistent with constructivism and follows the principle of induction by going from the macro to the submicro level. Note that the opposite approach, which starts from the structure of matter and follows a productive/receptive approach model, is quite common in chemistry education.

Georgiadou and Tsaparlis (2000) proposed and tried a three-cycle method, which goes separately over the macro, the representational and the submicro levels. In the macro cycle, which occupied half of the teaching time, the students became familiar with chemical substances and their properties. Central here was the use of experiment, while chemical notation as well as atoms and molecules were not included. Applying the spiral curriculum, the representational cycle covered the same course material, but added chemical formulas and equations. Finally, the submicro cycle brought atoms and molecules into play. Evaluation of the method, by end-of-school-year tests as well as by beginning-of-next year repeat of the same tests, showed that the three-cycle method made the largest single positive effect, compared with a traditional control class and a class in which teaching methods proposed by psychologist R. Case were applied.

Toomet, DePierro, and Garafalo (2001) developed a freshman chemistry curriculum, in which the topic of atomic structure is delayed until the second semester. In this curriculum, concept development is linked to the observable behaviour of matter, while the submicroscopic and symbolic realms are introduced by engaging students in some of the detective work that established the relative atomic masses of the elements and formulas of simple compounds. On the same line, Nelson (2002) discussed a way for teaching chemistry progressively, starting with observations at a macroscopic level, interpreting these at an atomic and molecular level and then at an electronic and nuclear level. Finally, Kolioulis and Tsaparlis (2007) wrote a textbook for eighth-grade chemistry with emphasis given to the macroscopic phenomena and concepts that are treated qualitatively using constructivist and meaningful-learning teaching methods, while the corpuscular concepts are delayed.

Chemistry is basically an experimental science, hence the contact, especially through the laboratory and practical work, with concrete examples of substances, their reactions and other properties, is an essential and integral part of chemical education. The laboratory is therefore the proper place for keeping chemistry tangible.

The Purposes and Aims of Practical Work

The terms *laboratory work* and *practical* work are used in the literature without precise definition to embrace numerous activities in science instruction. According to Hodson (1990), the term ‘practical work’ means tasks in which students observe or manipulate real objects or materials for themselves (individually or in small groups) or by witnessing teacher demonstrations. In an extended sense, practical work involves not only work in the formal chemistry laboratory or demonstrations, but also any type of activity that involves tangible objects, and provides students the opportunity to manipulate and interact with chemicals and observe chemistry in action; consequently, home laboratory kits and computer simulations of experiments are also included.

The statement of the purposes and the aims of laboratory activities is very useful for course designers and for teachers. On the other hand, detailed objectives guide teachers and students systematically in their work (Sutton, 1985). It is generally accepted that the main purposes of laboratory work are to teach hand skills and to illustrate theory (Hirvonnen & Virii, 2002). On the other hand, the aims of such work can be classified in two categories: (i) teaching the content of science; (ii) teaching about the methods of science (Leach, 1998). According to Hodson (1990), practical work can: motivate students by stimulating interest and enjoyment; teach laboratory skills; enhance the learning of scientific knowledge; give insight into scientific method and develop expertise in using it; develop ‘scientific attitudes’, such as open-mindedness and objectivity.

Numerous attempts have been made to articulate the aims (Johnstone & Al-Shuaili, 2001; Kerr, 1963). Meester and Maskill (1994), Laws (1996) and Bennett and O’Neale (1998) have in particular addressed the aims for the tertiary situation. Laboratory activities involve four major phases (Buckley & Kempa, 1971; Kempa & Ward, 1975) where students show responsibility for (a) planning and designing an investigation, (b) experimental investigation involving manipulative tasks, (c) observation of changes, (d) interpretation and explanation of data. The affective aims mentioned by Kerr (1963) are also important: interest in the subject; enjoyment of the subject; a feeling of reality for the phenomena talked about in theory. Further, one should distinguish between attitudes to science and scientific attitudes (Gardner & Gauld, 1990). Attitudes to science include interest, enjoyment, satisfaction, confidence and motivation. Scientific attitudes apply to styles of thinking such as objectivity, critical-mindedness, scepticism and willingness to consider the evidence (Garnett, Garnett, & Hackling, 1995).

Laboratory activities have the distinct advantage of engaging both the students’ psychomotor and the cognitive domains of learning. They begin with the employment of simple motor skills and proceed to sophisticated process skills. Hirvonnen and Virii (2002) reported that the theory–practice link was ranked highest by physics student teachers, followed by learning experimental skills, methods of scientific thinking, increased motivation and the opportunity for the teachers to evaluate students' knowledge; also, laboratory work could foster student teachers' understanding of physics. On the other hand, White et al.'s (1995) research, involving tertiary physics students, suggested that although students gained experimental skills from laboratory classes, their experiences were not always enjoyable and did not always contribute to their understanding of physics. Johnstone and Al-Shuaili (2001) have made a detailed discussion of the literature on manipulative and observational skills. Of particular importance is the skill of planning experiments that conventional laboratories tend to omit. Linked to this aim are the skills of problem solving at the bench.

A content analysis of 11 general chemistry laboratory manuals was carried out by Domin (1999a) and concluded that the majority require the learners to operate predominantly at the three lower cognitive levels of Bloom's taxonomy (knowledge, comprehension and application), leaving out the three higher levels of analysis, synthesis and evaluation.

Laboratory Instructional Types

Significant problems have been identified in the science education literature about the laboratory/practical courses, in particular about the ineffectiveness of laboratory instruction in enhancing conceptual understanding (Hofstein, 2004; Hofstein & Lunetta, 1982; 2004). The type of laboratory instruction plays certainly an important role in this deficiency.

There exist various types of distinct styles of laboratory instruction (Domin, 1999b): *expository, inquiry, discovery* and *problem-based.* According to Domin, these styles can be differentiated by their (i) outcome, (ii) approach and (iii) procedure. The outcome of any laboratory activity is either pre-determined or undetermined. Expository and problem-based activities typically follow a deductive approach, while discovery and inquiry activities are inductive. Lunetta (1998) distinguishes the various forms according to two aspects: (1) the extent of external guidance by the instructor and/or the manual, leading to (i) structured forms with detailed prescription of the student activities, or (ii) open forms that allow students a range of personal involvement and (2) the spectrum of activities that can vary from only setting up the experiment to including a complete inquiry sequence.

The Traditional Expository Laboratory

The most commonly applied style of laboratory instruction is the expository one, which is instructor-centred. The learner has only to follow the teacher's instructions or the procedure (from the manual). The outcome is predetermined by the teacher and may also be already known to the learner. The results of the experiments are compared with the expected results, so there is not the challenge to predict (Pickering, 1987). The expository laboratory satisfies the need to minimize resources, particularly time, space, equipment and personnel (Lagowski, 1990).

Despite this efficiency, expository instruction has been criticized for placing little emphasis on thinking: its ‘cookbook’ nature emphasizes the mechanical following of specific procedures to collect data, in order to verify or demonstrate principles described in textbooks. In this way, it is an ineffective means of building concepts and unrealistic in its portrayal of scientific experimentation (Byers, 2002), while little meaningful learning may take place (Johnstone & Wham, 1982). Such laboratory experiences lead only to lower-taxonomic level gains (McRobbie & Thomas, 2001) and facilitate the development of lower-order cognitive skills, such as rote learning and algorithmic problem solving (Meester and Maskill, 1994). Also, they ‘have little relevance to real life and so fail to promote in students a genuine interest and motivation for practical work’ (Johnstone & Al-Shuaili, 2001, p. 49).

Inquiry Laboratory (Open-Inquiry)

Inquiry-based activities have an undetermined outcome and require the learners to generate their own procedures. Students have to deal with a scientific problem, for the solution of which they must plan and carry out an experimental investigation, and reach a conclusion, which is communicated in some form (Garnett, Garnett, & Hackling, 1995; Hackling & Garnett, 1995). Therefore, the inquiry laboratory is more student-centred, contains less direction and gives the student more responsibility for determining procedural options than the traditional format. It effectively gives students ownership of the laboratory activity, which can result in the students’ showing improved attitudes towards laboratories. Such ownership requires learners to formulate the problem, relate the investigation to previous work, state the purpose of the investigation, predict the result, identify the procedure and perform the investigation. In addition, this type of laboratory has the potential to develop students’ abilities and skills such as: posing scientifically oriented questions, forming hypotheses, designing and conducting scientific investigations, formulating and revising scientific explanations and communicating and defending scientific arguments (Hofstein, Navon, Kipnis, & Mamlok-Naaman, 2005; Krajcik, Mamlok, & Hug, 2001).

Although inquiry-based practical work can foster many of the aims, it is time-consuming, potentially costly and very demanding on those who have to organize large laboratory classes. However, there is a strong case for its use from time to time and at all levels, as a short inquiry, attached to the end of an expository laboratory, using the skills and knowledge gained in the laboratory but with no fixed instructions (Johnstone & Al-Shuaili, 2001).

In his review of laboratory instruction styles, Domin (1999b, p. 546) states that

> because each style of laboratory instruction affects the learning environment in distinct ways, difference should be apparent with respect to learning outcomes.

He goes on by citing research studies that compared the various styles of laboratory instruction. Finally, he concluded that to better understand the effectiveness of each style, research should address not merely student achievement, but also the following specific learning outcomes: conceptual understanding, retention of content knowledge, scientific reasoning skills, higher-order cognition, laboratory manipulative skills, better attitude towards science and a better understanding of the nature of science.

Some relevant work on the chemistry laboratory at tertiary level which used inquiry-type work and/or collaborative learning is that by Hunter, Wardell, and Wilkins (2000), Rudd II, Greenbowe, Hand, and Legg (2001), Vallarino, Polo, & Esperdy (2001), Shitbley & Zimmaro (2002), and Byers (2002). These studies reported in general the effectiveness of the proposed methods. For instance, students seemed to develop critical judgment in the planning and performance of their work, gained confidence and skills in the use of instruments and developed abilities in technical writing (Vallarino, Polo, & Esperdy, 2001); a more positive attitude about the laboratory and about chemistry in the collaborative learning sections (Shitbley & Zimmaro, 2002); interest and motivation, as well as deeper thinking about the experiments before they were carried out, and deeper reflection on the results than was usually found with recipe-following procedures (Byers, 2002). Note that to distinguish among levels of inquiry, Fay, Grove, Towns, & Bretz (2007) evaluated a number of experiments and reported a diversity of uses of the term 'inquiry'.

Totally expository laboratories miss some of the desirable aims of laboratory work belonging to the receptive forms of teaching and learning. The reform movement in science education, which is based on standards (National Research Council, 1996; 2000), recommends a break away from exclusively receptive instruction. On the other hand, totally inquiry laboratories are currently probably impracticable not only in schools but also in universities. Nevertheless, Johnstone and Al-Shuaili (2001, p. 49) supported the idea that 'a core of expository laboratories with substantial "inserts" of inquiry will go a long way towards achieving the desirable aims of laboratory work'.

Project-Based Laboratory Instruction

The limitations of the conventional expository style of laboratory as well as the difficulties in realizing inquiry-based activities can be addressed in project-based activities that, without calling for new procedures, require students to try a modern experiment.

Tsaparlis and Gorezi (2005, 2007) have proposed the addition of a project-based component to a conventional expository physical chemistry laboratory. Project-type tasks were used, mainly taken from articles in *the Journal of Chemical Education.* During the performance of the project experiments, students were dedicated, patient and enthusiastic. The writing of the report and the oral presentation of the project were very demanding tasks. The evaluation of the work by the students through written questionnaires showed that the large majority was in favour of collaborative work. Working in groups of four was acceptable. On the other hand, the uneven contribution of the members of the group appeared to be a serious problem. Project work was judged superior for the development in students of communication skills (searching and using English literature, public presentation, collaboration, etc.), and of abilities related to the psychology of learning. Finally, the connection of chemistry with everyday life and modern applications (such as lithium batteries, commercial soaps and corrosion of metals) proved to be very attractive. Needless to add that to be effective, project work must be extended to all practical courses.

Underlying Pedagogy for Effective Practical Activities

There are many arguments from the literature that support new methods of learning in the laboratory (Hofstein & Lunetta, 2004). Experiences in the laboratory can provide opportunities for *constructing* knowledge, by engaging students intellectually with meaningful investigative experiences (Penner, Lehrer, & Schauble, 1998; Roth & Roychoudhury, 1993; Trumper, 2003).

It is widely accepted nowadays that science education supports a *constructivist* approach to teaching and learning. According to Vygotsky (1962), the learner constructs actively his/her knowledge, but this process is greatly assisted by interactions with peers and with the teacher who acts at the students' *zone of proximal development*. Shilandd (1999) examined the implications of constructivism for laboratory work. A social constructivist framework has special potential for guiding teaching in the laboratory (Hofstein & Lunetta, 2004; Trumper, 2003). Also, it may enhance positive attitudes and cognitive growth (Lazarowitz & Tamir, 1994). Note that the social environment in a laboratory is usually less formal than in a conventional classroom or lecture theatre. According to Millar and Driver (1987), the extended reflective investigations can promote the construction of more meaningful scientific concepts, based upon the unique knowledge brought to the science classroom by individual learners in dialogue with peer investigators. The role of the instructors is also crucial: according to Polman (1999), the teachers who wish to foster science learning through projects and inquiry must play a complex role in the discourse with their students. Gunstone and Champagne (1990) considered it necessary for meaningful learning to occur that students are given sufficient time and opportunities for interaction and reflections in the laboratory, as well as to take control of their own learning in the search for understanding.

Of particular interest is the possible connection of the nature-of-science (NOS) and the learning beliefs of the students with their type of practical work (Pomeroy, 1993). The NOS beliefs relate to the students' 'positivist' or 'post-positivist' science epistemologies. Students with a positivist view of science regard it as a 'logical and systematic collection of facts' (Tsai, 1998) or as a body of knowledge to be discovered by empirical means (Wallace, Tsoi, Calkin, & Darely, 2003). These same students may also prefer *traditional* learning strategies that are based on *lower-order cognitive skills* (LOCS; Tsaparlis & Zoller, 2003; Zoller, 1993;

Zoller & Tsaparlis, 1997), including rote learning and application of routine procedures and algorithms. Students with post-positivist NOS beliefs do not see science as a fixed collection of facts, but allow for compromises and errors, leaving room for changes and developments. On the other hand, there are those students who exhibit a preference for constructivist types of learning, such as understanding, explaining, predicting, planning and connecting. These latter students often have post-positivist NOS beliefs.

Phases in Laboratory Instruction

Lunetta (1998) has proposed a four-phase sequence for laboratory instruction: (i) planning-and-design, (ii) performing the experiment, (iii) analysing and interpreting the data and (iv) applying the acquired conceptual and procedural knowledge to new research questions. Doran, Lawrenz, and Helgeson (1994) have suggested a similar approach in which the previous last two phases are joined, resulting in three phases: (i) pre-experimental, (ii) experimental, (iii) post-experimental.

Reid and Shah (2007) have provided evidence supporting pre-laboratory exercises. However, pre-experimental activities constitute a phase that most often is missing from laboratory instruction. According to research findings, only about 3% of the laboratory time is applied to developing research questions for experiments (Tobin & Capie, 1982; Neber & Heumann-Ruprecht, 2006).

To develop such questions, and hence to realize the pre-experimental phase as a meaningful learning activity, students need to activate their domain-specific knowledge (Klahr, 2000; Neber & Anton, 2008). Neben and Anton have considered a sequence of five procedural steps that are necessary for the pre-experimental phase: Observation/phenomenon → Access to prior knowledge → Epistemic question(s) → Anticipated answer(s) → Planning for evidence.

Finally, of paramount importance for the proper interpretation of laboratory observations is the knowledge of the relevant theory. Hodson (1986) maintained that observations are theory-dependent and therefore fallible and biased. Even scientists themselves hold preconceptions and biases about the way the world operates, and these affect their ability to make observations ('theory-laden observations'). According to Johnstone and Al-Shuaili (2001, p. 47) 'investigation is very knowledge dependent and cannot take place in a knowledge vacuum.' As a result, 'students who lack the requisite theoretical framework will not know where to look, or how to look, in order to make observations appropriate to the task in hand, or how to interpret what they see' (p. 44).

Problem Solving and the Laboratory

Problem solving is well known as a composite activity involving various cognitive functions that depend on the number and quality of available operative schemata in long-term memory (see below) and on working memory capacity (Stamovlasis &

Tsaparlis, 2001; Tsaparlis, 1998; Tsaparlis & Angelopoulos, 2000). A real/novel problem requires that the solver must be able to use what has been described as higher-order cognitive skills (HOCS) (Tsaparlis & Zoller, 2003; Zoller, 1993; Zoller & Tsaparlis, 1997). A more thorough classification of problem types has been made by Johnstone (Johnstone, 1993; Tsaparlis & Angelopoulos, 2000).

Among the aims for practical work listed by Kerr (1963) is that of giving training in problem solving. Using demonstrations (and laboratory experiences in general) as an assessment tool, Bowen and Phelps (1997) reported that demonstrations not only oriented students' attention towards learning but also improved their problem-solving capabilities, helping them switch between various forms of representing problems dealing with chemical phenomena (for instance, symbolic and macroscopic). Along the same line, Deese, Ramsey, Walczyk, & Eddy (2000) found that demonstration assessments promoted critical thinking and deeper conceptual understanding of important chemical principles. Welzel (1999) maintained that problems are interesting to students when they can connect them to their experiences from everyday life. Finally, Zoller and Pushskin (2007) discussed the matching of HOCS promotion goals with problem-based laboratory practice in a freshman organic chemistry course.

Domin (2007) has carried out a study in which 15 students were interviewed after having experienced the first semester of laboratory instruction of a year-long sequence of general chemistry in a problem-based format, followed by a semester in which the laboratory portion of the course was taught in a traditional manner. For problem-based learning, conceptual development was maximized during the activity while in the laboratory. In the expository environment, however, it was maximized outside the laboratory, after the experiment had been completed. In a similar manner, Mc Donnell, O'Connor, and Seery (2007) used problem-based learning of mini projects as an alternative to the traditional 'recipe-style' laboratory because these reflect real-life problem solving situations. Small groups of students (three to four) who were assigned a project title and devised the experimental protocol to carry it out responded favourably on these laboratory classes.

Kampourakis and Tsaparlis (2003) have used a laboratory/practical activity, involving the well-known ammonia-fountain experiment, in order to find out if it can contribute to the solution of a demanding chemistry problem on the gas laws. Furthermore, they explored the extent to which the practical activity (which was performed by the students working in small groups), together with the follow-up discussion/interpretation in the classroom, could contribute to the improvement of the problem-solving ability of the students. A relatively low improvement in performance for many students was observed, and this was explained by the fact that the fountain experiment was very involved, having a potential for working-memory overload (see below). Also, its quite dramatic visual impact may have not permitted students to make too much sense of the underlying physical and chemical events. It is certainly open to question to what extent experimental work contributes easily to the ability in solving conceptually demanding problems. This is an area that merits further research.

Another contributing factor to students' low performance was the fact that those who participated in the study did not have a good understanding of the concepts that related to the ideal gas equation. This finding agrees with Kautz, Lovrude, Herron, and McDermott (1999) who pointed out that first- and second-year undergraduate students who attended traditional lectures had not developed functional understanding of the ideal gas and the ideal gas law. Also, as is the case with students in many countries, the students had no previous experience in working with chemicals and carrying out, or even watching, experiments. It may then be the case that this contact with chemical experiments had so much attracted their attention that little opportunity, during the experiments, was left for a mental processing of what was going on and why.

In conclusion, Kautz et al. suggested that the theory of chemistry and chemistry experiments *might* constitute two minimally overlapping spaces, and this can be coupled with a similar research finding (Hart, Mulhall, Berry, Loughran, & Gunstone, 2000). Further, it *might be* that *science problems and the concepts that enter the problems may constitute two minimally inter-connected/overlapping spaces*, especially in the case of complicated experiments. This finding reinforces the argument of Gabel, Sherwood, and Enochs (1984) that students who do not understand a concept qualitatively are likely to handle the mathematical equations thoughtlessly.

Simplifying the experimental setting, by using ready liquefied ammonia (from a lecture bottle, with a manometer attached to it) may help reduce the 'noise' and make students concentrate on the actual relevant phenomena. On the other hand, the use of computer simulations is promising with such problems. In any case, chemical educators must take into account the available possibilities and carefully choose their experiments, so that they first use simple experiments that involve few concepts.

Laboratory and Information Processing

What was of higher interest in the Kampourakis and Tsaparlis study (2003) was the fact that the chosen practical activity was very involved. The fountain experiment is indeed a spectacular and impressive one, but this feature may be the cause of the failure of most students to pay attention to the stimuli relevant to the problem. Indeed, one could argue that the relevant to the problem stimuli were not the dominant stimuli of the experiment. In particular, the generation of ammonia in the flask was also producing working memory space overload (see below).

Laboratory experiments and demonstrations are often complicated, posing a large demand on the student's capacity to process information. To introduce the concept of chemical reaction, de Vos and Verdonk (1985, p. 238) suggested that experiments are needed that 'could intrigue purely by the change of substances to other substances and that would not display any distracting phenomena. (On the contrary) fascinated (and blinded) by the bright light of burning magnesium, students fail to notice the white powder that is left behind by the process'. Similarly, Kempa and Ward (1988) reported observational limits of 'detectability' for several single stimulus and multi-stimuli observation tasks in secondary level chemistry. They provided tables of actual results obtained including type of observation, chemical system used, method of determining stimulus magnitude and observational thresholds. Students failed to notice or record one in every three observations.

Al-Shuaili (cited in Johnstone & Al-Shuaili, 2001, p. 44) showed that ‘the dominant stimulus may have to be played down if it is in danger of masking other important observations. This does not imply that the teacher should give all the answers before the laboratory, but rather prepare the observational faculties for what is to come’. A further complication to observation is that apparatus often masks a phenomenon. Johnstone and Al-Shuaili (2001) recommended that teachers should explain apparatuses so that the class can focus attention on the phenomenon.

Information Processing Model

Of particular relevance to the above discussion is the way in which learners initially handle incoming information such as that presented in a lesson, a lecture demonstration or during laboratory instruction. The new information is perceived and filtered in terms of what the learner already knows and can understand. As a result, information is not transferred intact from the mind of the teacher to the mind of the learner. It undergoes an initial selection (filtration) process and what is admitted will vary from person to person. Students with a similar background will tend to select in a similar, but not identical, way (Johnstone, 2007). An information-processing model is presented in Fig. 5.1.

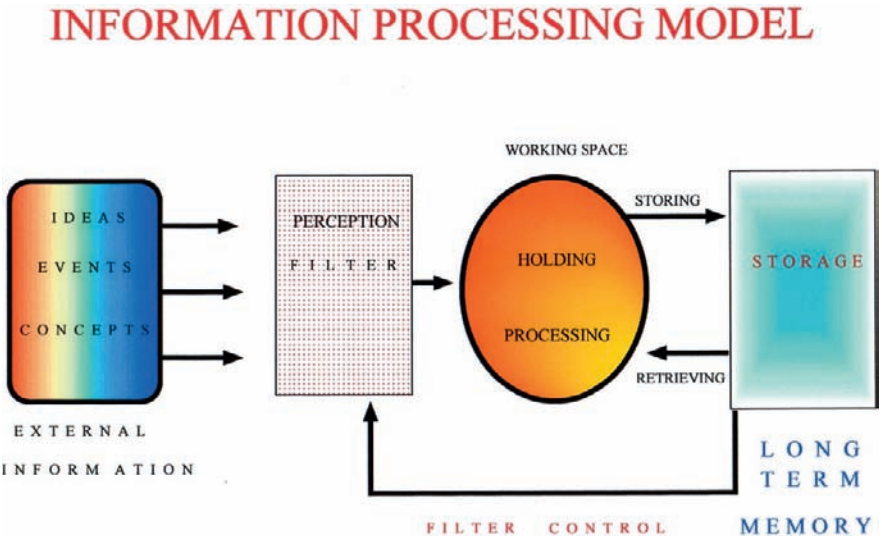


Fig. 5.1 The information processing model (from Johnstone, 2007, with permission)

The information admitted through the filter goes into *working space* (or *working memory*), the part of the mind where new information interacts consciously with what is already known and understood, with the aim of processing it into a form which can be stored for later use (or it can be rejected and discarded as being of no further use because it makes ‘no sense’). However, this working space has a severe limit upon the amount of information it can hold and process at any one time. For most people, the maximum number of pieces of information or operations, which can be successfully manipulated at one time, is five. In summary, there are a number of messages from research that, if applied, would make students’ experience of laboratory instruction more meaningful, enjoyable and yet intellectually demanding and satisfying (Johnstone, 2007):

- What we learn is controlled by what we already know.
- Learners can process only a limited amount of information at one time.
- Science concepts exist on more than one intellectual level.
- Many scientific concepts are of a different kind from everyday concepts.
- Learners need to start with concepts built from tangible experience and developed later to include inferred concepts.

Context-Based Approaches to Practical Work

Context-based approaches to teaching and learning chemistry provide applications as starting points from which to develop the subject. Their success is attributed, at least in part, to higher levels of interest and motivation amongst the students, together with their perception of the relevance of the topics (Gutwill-Wise, 2001). Experimental activities constitute an integral part of all context-based chemistry curricula.

Gilbert (2006) has considered the nature of ‘context’ in chemical education and has identified four generic models of ‘context’ as basis for curriculum design and development: context as direct application of concepts; context as reciprocity between concepts and applications; context as provided by personal mental activity; and context as social circumstances. Of particular importance for the use of contexts, Gilbert considers three approaches to the making of meaning, each building on its predecessor: constructivism, situated learning and activity theory. Context-based approaches are also consistent with Novak’s theory of human constructivism (Bretz, 2001; Novak, 1998).

Context-based curricula developed in five countries were reviewed in a special issue of the *International Journal of Science Education* (2006, Vol. 28, Number 9). Schwartz (2006) discussed the American experience with *ChemCom: Chemistry in the Community*, and mainly with *Chemistry in Context* (CiC). Bennett and Lubben (2006) presented *Salters Advanced Chemistry* that was developed in Britain. Hofstein and Kesner (2006) reported on Israeli materials focusing on industrial chemistry as the main school chemistry theme. Parchmann et al. (2006) considered the German contextual version, *Chemie im Kontext* (ChiK). Finally, Bulte,

Fig. 5.2 An instance from the experiment with the toothpaste (*left*). An enthusiastic student (*right*) shows to students of another group the result of her experiment with bath-bubblers. (Photos by author.)

Westbroek, de Jong, and Pilot (2006) reported on a Dutch research approach using authentic practices as contexts. It is notable that some of the above approaches have been adopted in a number of other countries.

Since September 1997, the *Journal of Chemical Education* (JCE) publishes on a regular base a 'Classroom Activity' that is set separately on a distinct hard sheet, including both the student activity (on one side) and instructor information sheet (on the back side). These activities are designed to actively engage students, while the topics covered are usually connected with everyday life and applications (e.g. acid rain, bath bubblers, toothpastes, water filtration, anthocyanins, latent fingerprints, etc.). Liapi and Tsaparlis (2007) have used three of these activities (acid rain, bath bubblers, toothpastes) in conjunction with two conventional laboratory activities (some properties of acids/some properties of bases) with a class of ninth-grade students in Greece. An evaluation by the students showed a very positive result in favour of the JCE Activities: they are connected with life and involve creativity on the part of the students (Fig. 5.2).

Lecture Demonstrations

Despite the fact that the students do not consider lecture demonstrations as effective as active performance of experiments as discussed previously, there is often the case that during experimental work vital observations are obscured by powerful, but less important stimuli. In such cases, demonstrations, rather than individual laboratory work, may be the best procedure. In a demonstration, the teacher has control and can focus attention on the salient observations (Johnstone & Shuaili, 2001) and demonstrations can also form the basis for providing a broader technique for assessment of learning (Bowen & Phelps, 1997).

According to Ashkenazi and Weaver (2007), lecture demonstrations can provide essential experiences that serve as a context for discussion of over-generalized or over-simplified concepts. The design of such demonstrations starts from surveying the limited knowledge base of the student, followed by exploration of the richness of relevant contexts of the expert, and identifying key instances that can serve as meaningful discussion topics. Very important is the introduction of discrepant events by demonstrating the unexpected behaviour of chemical systems (Bodner, 2001; Zimrot & Ashkenazi, 2007). Ashkenazi and Weaver have given an example of the design of a demonstration set for teaching solvent miscibility and its relation to intermolecular interaction, followed by results of its application in two different presentation modes: (i) *confrontation* which aims at generating a conflict with existing conceptions; and (ii) *refinement* which aims at promoting differentiation and contextualization of scientific concepts.

Interactive Lecture Demonstrations (ILD) involve a student-centred teaching method, in which students are asked to predict the outcome of an experiment, observe the outcome and discuss it with respect to their former expectations (Zimrot & Ashkenazi, 2007). The demonstrations were designed to contradict students' misconceptions, and promote conceptual change through cognitive conflict and dissatisfaction with the existing conception. In a relevant study, three major levels of conceptual change were identified: high – students who remember the outcome of the demonstration, and explain it using the consensus model; medium – students who can recall the outcome, are dissatisfied with their alternative model, but do not switch to the consensus model; and low – no meaningful recollection of the outcome, and no change in the alternative model. An experimental group of students was compared with another group that only observed the demonstrations, without predicting and discussing. A significant difference was found, with an obvious drop in students' ability to recall the outcome of the demonstrations in the non-interactive group.

Students' Cooperative Practical Work

A major conclusion of science education research is that active-learning methods of teaching and learning should replace traditional didactic methods. Active learning may be implemented by students working on their own (under the instructor's observation and guidance), but more effectively by students working together in small groups: of four or five to accomplish an assigned common learning task/goal (Flynn & Klein, 2001). According to Byers (2002, p. 32), 'discussion in peer groups through the pre-lab and post lab sessions encourages deeper thinking about experiments before they are carried out and deeper reflection on the results than is usually found with recipe-following procedures'. For a bibliography on cooperative learning, see Nurrenbern and Robinson (1997).

Active and cooperative learning methods are consistent with *social/cultural constructivism*, provide a better learning environment and contribute to deeper understanding and development of learning skills (Duncan-Hewitt, Mount, & Apple, 1995; Johnson, Johnson, & Smith, 1991). This form of learning is traditionally used in laboratory work. It was also used in the project-enriched physical chemistry laboratory described above (Tsaparlis & Gorezi, 2005; 2007).

A crucial issue in cooperative work is the *dynamics* within the group (Stamovlasis, Dimos, & Tsaparlis, 2006). Each individual engaged in such work may play three roles: the *learner*, the *learner facilitator* and the *leader.* Important is also the interaction mechanism that focuses on a *synergetic effect* among individuals. It is reasonable to suggest that under certain conditions (cognitive and affective ones) there is a possibility that the outcome of working in groups could surpass individual capabilities because cross-fertilization occurs between interacting peers. In any case, the extent to which cooperative work promotes an individual's acquisition and retention of learned material depends on many factors, such as: the individual differences of the group members, the nature of the task, the process itself and prior training in group-skills. The unequal contribution of the members of the group appears to be a very serious problem of cooperative work – it occurred with about one third of the students in the physical chemistry laboratory projects (Tsaparlis & Gorezi, 2005; 2007).

Linking the Macro with the Micro in the Laboratory

Numerous studies have shown that students have great difficulties when trying to grasp concepts such as that of the molecule and the atom, i.e., when trying to move from the macro to the submicro level, and vice versa. Various researchers (e.g. Abraham, Williamson, & Westbrook, 1994; Brook, Briggs, & Driver, 1984, Haidar & Abraham, 1991, Lee, Eichinger, Anderson, & Berkheime, 1993, Novick & Nussbaum, 1981) have investigated students' alternative conceptions. Herron (1978), Johnstone (1991) and Tsaparlis (1997) have stated the position that students have difficulties with concepts and topics relevant to the structure of matter.

Laboratory instruction is often presented at the macro level, with the basic aim to demonstrate laws and phenomena. Theory and the submicro level are then invoked to explain observations at the macro level, but experiments that demonstrate directly the macro–submicro link are lacking. The connection among the three levels of chemistry will contribute greatly to the development of thinking abilities in students (Georgiadou and Tsaparlis, 2000; Johnstone, 2000), but this connection is a hard task as the following anecdotal evidence from a lesson on oxygen to eighth-grade students in a Greek urban school demonstrates. The teacher set fire to a quantity of sulfur in a porcelain crucible, and asked the student to describe what he had observed:

Student: The sulfur caught fire and smoke was created.
Teacher: Can you write on the chalkboard the chemical equation for the reaction?

The student then wrote $S + \ldots$, the teacher added O_2, and the student completed successfully the equation $\rightarrow SO_2$.

Teacher: Very well. Could you describe again what you had observed before?
Student: The sulfur caught fire, and oxygen went along with it, and . . .

Extensive and careful experimentation is actually required to demonstrate the involvement, isolation and identification of gases in chemical reactions.

Gases and the Importance of History of Chemistry

The above evidence brings us to the importance of experimentation with gases for the understanding of chemistry, and the desired connection with the representational/symbolic and submicro levels. History of chemistry is of paramount importance here. First, tribute must be paid to the great contribution to the role of the experiment in chemistry by Robert Boyle (1627–1691). Consequently, a diversion to the history of the study of gases is deemed essential.[2]

Most chemists left gases unaccounted for from the years of alchemy until the beginning of the eighteenth century. ‘Airs’ or ‘gases’ were not considered as a variety of chemical species. The reason was that chemists did not have the means to examine and measure gases as they did with solids and liquids. In the Encyclopedia of Didorit and D’Alembert (Encyclopedie, 1757, 7, p. 520) it was stated: ‘the incoercibiltiy of gases will remove them from our researches for a long time to come’.

It took many years and the genius of various scientists for gases not only to take up their proper place in the study of chemistry, but also to provide the means for making the chemical revolution and establishing chemistry as a real science. The conception and construction of innovative appropriate equipments was a *sine qua non* for the study of gases. To study ‘that wonderful fluid, which is of such importance to the life of plants and animals’, Stephen Hale devised in 1727 his *pneumatic trough* (Levere, 2001, p. 53). Joseph Black’s (1727–99) studies were considered a model for the investigation of ‘airs’. Cavendish (1731–1810) repeated some of Black’s experiments, adding his own quantitative observations. Joseph Priestley (1733–1804) discovered new kinds of air, including carbon dioxide (fixed air) and oxygen. His pneumatic apparatus (Levere, 2001, p. 58) was highly functional and simple. Finally, Antoine-Laurent Lavoisier (1743–1794) proposed the oxygen theory of combustion, overthrowing the phlogiston theory. Indeed, gases were central to Lavoisier’s chemical revolution and the composition of water was one of his key experiments. For this investigation, he invented the *Gasometer* (Fig. 5.3), an instrument that according to him was indispensable for all kinds of work in pneumatic chemistry. The vast amount of data that this pneumatic chemistry brought about provided John Dalton the tool to develop the atomic theory, thus connecting the macro level of chemistry with the submicro one. The representational mode was also of great help, so it is not strange that Dalton had invented atomic symbols (Levere, 2001, p. 86).

---

[2] For a full account, see Levere’s book on the history of chemistry (Levere, 2001), from which information is borrowed in the present context.

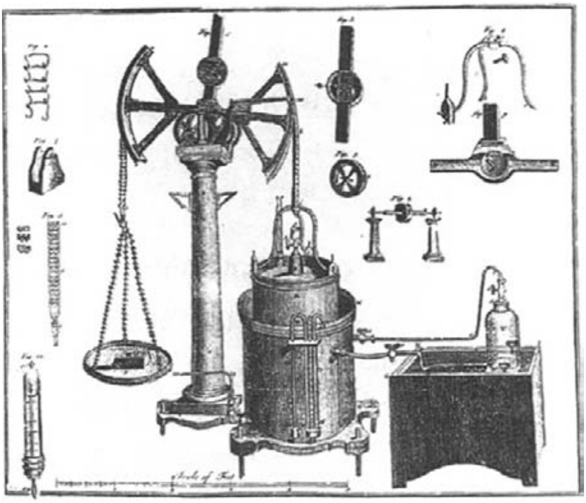


Fig. 5.3 Lavoisier's gasometer (from Antoine-Laurent Lavoisier, Traité élémentaire de chimie, 2 vols., Paris, 1789, plate 8)

Building the Particulate Model of Matter: Macro–Micro Relationships

Returning to the modern era, mention must be made of an international seminar that was dedicated to the relation of macroscopic phenomena to submicroscopic particles (Lijnse, Licht, DeVos, & Warlo, 1990). Ben-Zvi, Silberstein, and Mamlok (1990) confirmed that the root of many difficulties held by beginning chemistry students are due to the deficient understanding of the atomic model and how it is used to explain phenomenology and the laws of chemistry. Appropriate models are also essential to explain the link between energy transfer and temperature change in chemical changes, as well as the link between the molecular model and the energy transfer. Having studied students' relevant views and the problems concerning macro–submicro relationships in the area of structure and reaction, the authors proceeded to propose a teaching unit to help overcome students' difficulties. The unit employed a well-known statistical-thermodynamics model, coupled with mechanical models, to explain the energy changes accompanying reactions.

Meheut and Chomat (1990) attempted to teach 13–14-year-old children how to build up a particulate model of matter by working out a sequence of experimental facts, starting from properties of gases (compression, diffusion), then moving on to solids, leaving the liquids last. On the other hand, Millar (1990) placed the emphasis on employing everyday contexts (on the basis of the Salters' approach: Hills, Holman, Lazonby, Raffan, & Waddington (1989), using, for example, a piece of cloth (which is made of fabrics, made of threads, made of fibres) to move from the macro to the submicro level.[3] Millar suggested that it might be wise to start with solids, and postpone consideration of gases until later: many children need time and experience to appreciate that gases are really matter.

Finally, in a collective volume, Nussbaum (1998), after critically reviewing the various relevant propositions from the 1990 international seminar, coupled the history-and-philosophy-of-science approach with the constructivist teaching of corpuscular theories. Vacuum physics is, according to Nussbaum, the right starting point for corpuscular physics. Only the existence of vacuum can justify incontinuity of matter, hence its corpuscular nature. In addition, vacuum allows for motion of the particles. Nussbaum based his introduction of the corpuscular model on the study of air and other gases, and maintained that the study of the corpuscular model is a long process of conceptual change, in which students' wrong ideas can play a positive role.

Though I subscribe to Nussbaum's position that the concept of vacuum is central for a conceptual understanding of corpuscular concepts, for younger students I am in favour of starting with solids and liquids, that are concrete and tangible, and leaving gases last (in agreement with Millar). Emphasis must be placed on discussing prerequisite physics concepts and techniques that are deemed essential for realising the above aim. Relevant to this issue is the text for eighth-grade chemistry, by Kolioulis and Tsaparlis (2007), in which the corpuscular concepts are delayed until the last third of the text and developed in seven lessons, namely: the concept of molecule in solids and liquids; ever-moving molecules; the concept of molecule in gases; the first two laws of chemistry [conservation of matter (Lavoisier) and constant proportions (Proust)]; the concept of atom (Dalton's atomic theory, law of multiple proportions; Gay-Lussac's experiment; Avogadro's hypothesis); chemical formulas and the mole concept; the concept of chemical equation.

Discussion and Prospects for the Future

The Importance of Practical Activities in Chemistry

A large amount of research has examined the effectiveness of laboratory work in science education in attaining cognitive, affective and practical goals (Hofstein & Mamlok-Naaman, 2007). Critical accounts and reviews are available in the literature (Blosser, 1980; Bryce & Robertson, 1985; Hodson, 1993; Hofstein & Lunetta, 1982; 2004; Lazarowitz & Tamir, 1994; Tobin, 1990). A sad finding is that research has failed to show simplistic relationships between experiences in the laboratory and student learning (Hofstein & Mamlok-Naaman, 2007).

---

[3] The use of a textile thread (the 'structural unit' of a piece of cloth) as well as of a brick (the 'structural unit' of a house's wall) as analogues of the structural unit of matter has also been used by Tsaparlis (1989).

It is expected that, in the future, inquiry, project-, problem- and context-based approaches will be given more emphasis. Cooperative forms of laboratory instruction must surely be further and systematically explored, taking into account the research-based recommendations. Lecture demonstrations, effectively designed and performed, will also be useful. Other nonconventional methods can be effectively employed, such as the use of home-laboratory kits to teach general chemistry through distance education (Kennepohl, 2007).

Expository-type laboratory activities will continue to be needed for the development of basic experimental skills of the students, despite their inefficiency in providing a realistic scientific environment and in promoting the use of higher-order cognitive skills. Even defenders of the conventional-type of laboratory and laboratory manual do not claim that they are always wisely used, nor do they claim that they should be used exclusively (Ault, 2002; 2004). However, the dominant problem is that despite the fact that research has established the superiority of inquiry laboratory activities over verification laboratory activities, cookbook laboratory activities are still prevalent in many high school and college institutions (Monteyne, Mark, & Cracolice, 2004).[4]

Reid and Shah (2007) argued that the place of experimental work needs to be reconsidered at higher education. Higher education must build on the skills that might have developed at school level. There should be re-thinking of the use of laboratory manuals, with assessment being explored afresh. Also, seeing the laboratory experience in the context of what goes on before and after, as well as other learning, would enhance the learning potential of this time.

Staying at the tertiary level, *Advancing Chemistry by Enhancing Learning in the Laboratory* (ACELL) is a new project (Buntine et al., 2007) that aims to build a database of experiments that are both chemically and educationally sound by testing them in a third-party laboratory. The journal *Chemistry Education Research and Practice* is starting a new feature with the publication of evaluations of ACELL experiments. The first experiment deals with thermodynamics in chemical change (Read & Kable, 2007).

The Contribution of Technology to Practical Work in Chemistry

The use of technology, and especially of computers, may contribute to better teaching and learning. For instance, Brattan, Mason, & Best (1999) used computer-based resources for supporting the first-year physical chemistry laboratory, and reported that students' abilities in planning and executing the experiments, and their attitude to laboratory work improved. It is generally expected that the use of models, simulations and animations may help students contradict and overcome common misconceptions. The *Journal of Chemical Education* (JCE) provides a full range of computerized instructional materials, including Web-based computations and animations.

---

[4] According to a survey by Abraham et al. (1997), only eight percent of ACS-accredited institutions used inquiry materials in lab.

The Importance of the Affective Domain

Educationists usually place the emphasis on the cognitive objectives of practical work. Of equal importance are however factors of the affective domain. Gott & Mashiter (1991, p. 61) proposed that practical tasks should 'have within them the elements of motivation that stem from confidence in and a sense of ownership of the activity by the student'. Motivation, however, requires not only a measure of self-directedness by the learner but also interesting and exciting experiments (Hodson, 1996).

Students' motivational styles play an important role in their attitudes towards practical work. Adar has distinguished among four student categories of motivational style: the curious, the conscientious, the achiever and the social (Adar, 1969; Hofstein & Kempa, 1985; Kempa & Diaz, 1990a). Curious students do not like to be passive learners and prefer to engage actively in their educational process through various activities, in our case inquiry and project-type of laboratories. Social students like collaborative environments very much. On the other hand, conscientious students have a preference for the more structural and directed expository laboratory (Kempa & Diaz, 1990b). Note that the classification of students in terms of the four motivational patterns does not imply that the patterns should be fully independent of each other; actually, a certain degree of overlap between the traits is found, and in particular a very strong link between 'curiosity' and 'consciousness' (Kempa & Diaz, 1990a).

Assessment and Standards in Practical Work in Chemistry

A very important issue that we did not deal with in this chapter is that of assessing practical work. Surely there is a need to actually assess practical experiences of all kinds, because if the students know that they will be tested on these, they will pay more attention (Bowen & Phelps, 1997; Deese et al., 2000). Kempa (1986) has considered that the following qualities should be taken into account in schemes for the assessment of practical abilities: (a) recognition and formulation of a problem, (b) design and planning of experimental procedures, (c) setting-up and execution of experimental work (manipulation), (d) observational and measuring skills (including the recording of data and observations), (e) interpretation and evaluation of experimental data and observations. Formative assessment is more appropriate to the extent that summative assessment might be redundant.

As a result of science education research, a new era of reform in science education has started with the new century. New standards have been fixed (National Research Council, 1996, 2000). The *National Science Education Standards* (National Research Council, 1996) and also the 2061 project of the *American Association for the Advancement of Science* (1989, 1990) assume that inquiry in general and inquiry in the context of practical work in science education is central to the achievement of scientific literacy (Hofstein & Mamlok-Naaman, 2007).

Practical activities should embody as best as possible the scientific processes that have been prescribed by the *American Association for the Advancement of Science*: observation, classification, numerical relations, measurements, time–space relations, communication (oral, pictorial, written), deriving of conclusions, prediction ('what would happen if . . .'), hypothesis making, production of operational definitions, identification and control of variables, experiment and explanation of experimental data. Different theoretical perspectives should be used with the aim to optimize the positive cognitive and affective outcomes. The use, sometimes together, sometimes separately, of different perspectives can act complimentarily and can lead to positive results (Niaz, 1993; Tsaparlis, 1997).

Improving Scholarship on Practical Activities

Finally, Hofstein & Mamlok-Naaman (2007) and Lunetta, Hofstein, & Clough (2007) have made a number of recommendations for prospective researchers of practical activities that can develop the quality of research and the applicability of its results. Researches should provide detailed descriptions of method, the participating students (their numbers and roles), teachers, classrooms and curriculum contexts in research reports. They should report if it is a long-term or a short-term investigation, the amounts of time students spend in laboratory activities, and how those are integrated or separated from other work in the science course. The following questions should also be addressed: What do the students perceive they are supposed to accomplish in the laboratory activity? How do they perceive their laboratory performance will be assessed? How important do the students and the teachers perceive the laboratory activities to be? Other variables include: learning objectives; the nature of the instructions provided by the teacher and the laboratory guide; materials and equipment available for use in the laboratory investigation; the nature of the activities and the student–student and teacher–student interactions during the laboratory work; assessment issues; students' laboratory reports; the preparation, attitudes, knowledge and behaviours of the teachers.

References

Abraham, M. R., Craolice, M. S., Palmer Graves, A., Aldhamash, A. H., Kihega, J. G., Palma Gal, J. G., & Varghese, V. (1997). The nature and state of general laboratory courses offered by colleges and universities in the United States. *Journal of Chemical Education, 74*, 591–594.

Abraham, M., Williamson, V., & Westbrook, S. (1994). A cross-age study of the understanding of five chemistry concepts. *Journal of Research in Science Teaching, 31*, 147–165.

Adar, L. (1969). *A theoretical framework for the study of motivation in education*. Jerusalem: The Hebrew University School of Education.

American Association for the Advancement of Science (1989 & 1990). *Project 2061: Science for all Americans*. Washington, DC.

Ashkenazi, G., & Weaver, G. C. (2007). Using lecture demonstrations to promote the refinement of concepts: The case of teaching solvent miscibility. *Chemistry Education Research and Practice, 8*, 186–196.

Ault, A. (2002). What's wrong with cookbooks. *Journal of Chemical Education, 79*, 1177.

Ault, A. (2004). What's wrong with cookbooks (author's reply). *Journal of Chemical Education, 81*, 1569.

Bennett, J., & Lubben, F. (2006). Context-based chemistry: The Salters approach. *International Journal of Science Education, 28*, 999–1015.

Bennett, S. W., & O'Neale, K. (1998). Skills development and practical work in chemistry. *University Chemistry Education, 2*, 58–62.

Ben-Zvi, R., Silberstein, J., & Mamlok, R. (1990). Macro-micro relationships: A key to the world of chemistry. In P. L. Lijnse, P. Licht, W. DeVos, & A. J. Warlo (Eds.), *Relating macroscopic phenomena to microscopic particles* (pp. 183–197). Utrecht: CD-β Press.

Blosser, P. (1980). *A critical review of the role of the laboratory in science teaching*. Columbus OH: Center for Science and Mathematics Education.

Bodner, G. M. (2001). Why lecture demonstrations are 'exocharmic' for both students and their instructors. *University Chemistry Education, 5*, 31–35.

Bowen, C. W., & Phelps, A. J. (1997). Demonstration-based cooperative testing in general chemistry: A broader assessment-of-learning technique. *Journal of Chemical Education, 74*, 715–719.

Brattan, D, Mason, D., & Best, A. J. (1999). Changing the nature of physical chemistry practical work. *University Chemistry Education, 3*, 59–63.

Bretz, S. L. (2001). Novak's theory of education: Human constructivism and meaningful learning. *Journal of Chemical Education, 78*, 1107.

Brook, A., Briggs, H., & Driver, R. (1984). *Aspects of secondary students' understanding of the particulate nature of matter*. University of Leeds: Centre for Studies in Science and Mathematics Education.

Bryce, T. G. K., & Robertson, I. J. (1985). What can they do? A review of practical assessment in science. *Studies in Science Education, 12*, 1–24.

Buckley, J. G., & Kempa, R. F. (1971). Practical work in sixth-form chemistry courses: An enquiry. *School Science Review, 53*(182) 24.

Bulte, A. M. W., Westbroek, H. B., de Jong, O., & Pilot, A. (2006). A research approach to designing chemistry education using authentic practices as contexts. *International Journal of Science Education, 28*, 1063–1086.

Buntine, M. A., Read, J. R., Barrie, S. C., Bucat, R. B. Crisp, G. T., George, A. V., Jamie, I. M., & Kable, S. H. (2007). Advancing Chemistry by Enhancing Learning in the Laboratory (ACELL): A model for providing professional and personal development and facilitating improved student laboratory learning outcomes. *Chemistry Education Research and Practice, 8*, 232–254.

Byers, W. (2002). Promoting active learning through small group laboratory classes. *University Chemistry Education, 6*,28–34.

Deese, W., Ramsey, L. L, Walczyk, J., & Eddy, D. (2000). Using demonstration assessments to improve learning. *Journal of Chemical Education, 77*, 1511–1516.

de Vos, W., & Verdonk, A.H. (1985). A new road to reactions, Part I. *Journal of Chemical Education, 62*, 238–240.

Domin, D. S. (1999a). A content analysis of general chemistry laboratory manuals for evidence of higher-order cognitive tasks. *Journal of Chemical Education, 76*, 109–112.

Domin, D. S. (1999b). A review of laboratory instruction styles. *Journal of Chemical Education, 76*, 543–547.

Domin, D. S. (2007). Students' perceptions of when conceptual development occurs during laboratory instruction. *Chemistry Education Research and Practice, 8*, 14–152.

Doran, R. L., Lawrenz, F., & Helgeson, S. (1994). Research on assessment in science. In D. Gabel (ed.), *Handbook of research on science teaching and learning* (pp. 388–442). New York, NY: MacMillan.

Duncan-Hewitt, W., Mount, D. L., & Apple, D. A. (1995). *A handbook on cooperative learning* (2nd ed.). Corvallis, OR: Pacific Crest.

Fay, M. E., Grove, N. P., Towns, M. H., & Bretz, S. L. (2007). A rubric to characterize inquiry in the undergraduate chemistry laboratory. *Chemistry Education Research and Practice, 8*, 212–219.

Flynn, A. E., & Klein, J. P. (2001). The influence of discussion groups in a case-based learning environment. *Education Technology Research and Development, 49*(3), 71–84.

Gabel, D. L., Sherwood, R. D., & Enochs, L. (1984). Problem-solving skills of high school chemistry students. *Journal of Research in Science Teaching, 21*, 211–233.

Gardner, P., & Gauld, C. (1990). Labwork and students' attitudes. In E. Hegarty-Hazel (Ed.), *The school laboratory and the science curriculum* (pp. 132–156). London: Routledge.

Garnett, P. J., Garnett, P. J., & Hackling, M. W. (1995). Refocusing the chemistry lab: A case for laboratory-based investigations. *Australian Science Teachers Journal, 41* (2), 26-32.

Georgiadou, A., & Tsaparlis, G. (2000). Chemistry teaching in lower secondary school with methods based on: (a) psychological theories; (b) the macro, representational, and submicro levels of chemistry. *Chemistry Education Research and Practice, 1*, 217–216.

Gilbert, J. K. (2006). On the nature of "context" in chemical education. *International Journal of Science Education, 28*, 957–976.

Gott, R., & Mashiter, J. (1991). Practical work in science: A task-based approach? In B. Woolnough (Ed.), *Practical science* (pp. 53–66). Buckingham, UK: Open University Press.

Gunstone, R. F. & Champagne, A. B. (1990). Promoting conceptual change in the laboratory. In E. Hegarty-Hazel (Ed.), *The student laboratory and the science curriculum* (pp. 159–182). London: Routledge.

Gutwill-Wise, J. P. (2001). The impact of active and context-based learning to introductory chemistry courses. *Journal of Chemical Education, 78*, 684–690.

Hackling, M. W., & Garnett, P. J., (1995). The development of expertise in science investigative skills. *Australian Science Teachers Journal, 41*(4), 80–86.

Haidar, A., & Abraham, M. (1991). A comparison of applied and theoretical knowledge of concepts based on the particulate nature of matter. *Journal of Research in Science Teaching, 28*, 919–938.

Hart, C., Mulhall, P., Berry, A., Loughran, J., & Gunstone, R. (2000). What is the purpose of this experiment? Or can students learn something from doing experiments? *Journal of Research in Science Teaching, 37*, 655–675.

Herron, J. D. (1978). Piaget in the classroom. *Journal of Chemical Education, 55*, 165–170.

Hills, G., Holman, J., Lazonby, J., Raffan, J., & Waddington, D. (1989). *Introducing chemistry: The Salters' approach*. London: Heinemann Educational Books.

Hirvonnen P. E., & Virii, J. (2002). Physics student teachers' ideas about the objectives of practical work. *Science & Education, 11*, 305–316.

Hodson, D. (1986). The nature of scientific observation. *School Science Review, 68*(242), 17–28.

Hodson, D. (1990). A critical look at practical work in school science. *School Science Review, 70*(256), 33–40.

Hodson, D. (1993). Re-thinking old ways: Towards a more critical approach to practical work in school science. *Studies in Science Education, 22*, 85–142.

Hodson, D. (1996). Laboratory work as scientific method: Three decades of confusion and distortion. *Journal of Curriculum Studies, 28*, 115–135.

Hofstein, A. (2004). The laboratory in chemistry education: Thirty years of experience with developments, implementation and evaluation. *Chemistry Education Research and Practice, 5*, 247–264.

Hofstein, A., & Kempa, R. (1985). Motivational strategies in science ecuation: Attempt at an analysis. *European Journal of Science Education, 7*, 221–229.

Hofstein, A., & Kesner, M. (2006). Industrial chemistry and school chemistry: Making chemistry studies more relevant. *International Journal of Science Education, 28*, 1017–1039.

Hofstein, A., & Lunetta,V. N. (1982). The role of the laboratory in science teaching: Neglected aspects of research. *Review of Educational Research, 52*, 201–217.

Hofstein, A., & Lunetta, V. (2004). The laboratory in science education: Foundations for the twenty-first century. *Science Education, 88*, 25–54.

Hofstein, A., & Mamlok-Naaman, R. (2007). The laboratory in science education: The state of the art. *Chemistry Education Research and Practice, 8*, 105–107.

Hofstein, A., Navon, O., Kipnis, M., & Mamlok-Naaman, R. (2005). Developing students' ability to ask more and better questions resulting from inquiry-type chemistry laboratories. *Journal of Research in Science Teaching, 42*, 791–806.

Hunter, C., Wardell, & Wilkins, H. (2000). Introducing first-year students to some skills of investigatory laboratory work. *University Chemistry Education, 4*, 14–17.

Johnson, D. W., Johnson, R. T., & Smith, K. A. (1991). *Active learning cooperation in the learning classroom*. Edina, MN: Interaction Book Co.

Johnstone, A. H. (1991). Thinking about thinking. *International Newsletter on Chemical Education, 6*, 7–11.

Johnstone, A. H. (1993). Introduction. In C. Wood & R. Sleet (Eds.), *Creative problem solving in chemistry* (pp. iv–vi). London: The Royal Society of Chemistry.

Johnstone, A. H. (2000). Teaching of chemistry – Logical or psychological? *Chemistry Education Research and Practice, 1*, 9–15.

Johnstone, A. H. (2007). Science education: We know the answers, let's look at the problems. *Proceedings of the 5th Greek Conference "Science education and new technologies in education"*, Vol. 1, pp. 1–11. [http://www.kodipheet.gr/fifth_conf/pdf_synedriou/teyxos_A/1_kentrikes_omilies/1_KO-4-Johnstone.pdf].

Johnstone, A. H., & Al-Shuaili, A. (2001). Learning in the laboratory: Some thoughts from the literature. *University Chemistry Education, 5*, 42–51.

Johnstone, A. H., & Wham, A. J. B. (1982). The demands of practical work. *Education in Chemistry, 19*(3), 71–73.

Kampourakis, C., & Tsaparlis, G. (2003). A study of the effect of a practical activity on problem solving in chemistry. *Chemistry Education Research and Practice, 4*, 319–333.

Kautz, C. H., Lovrude, M. E., Herron, P. R. L., & McDermott, L. C. (1999). Research on student understanding of the ideal gas law. *Proceedings, 2nd International Conference of the European Science Education Research Association* (*ESERA*), *Kiel, Germany, 1*, 83–85.

Kempa R. (1986). *Assessment in science* (Ch. 5). Cambridge: Cambridge University Press.

Kempa, R. F., & Diaz, M. M. (1990a). Motivational traits and preferences for different instructional modes in science – Part 1: Students' motivational traits. *International Journal of Science Education, 12*, 195–201.

Kempa, R. F., & Diaz, M. M. (1990b). Students' motivational traits and preferences for different instructional modes in science education – Part 2. *International Journal of Science Education, 12*, 205–216.

Kempa, R. F., & Ward, J. E. (1975). The effect of different modes of task orientational attainment in practical chemistry. *Journal of Research in Science Teaching, 12*, 69–76.

Kempa, R. F., & Ward, J. E. (1988). Observational thresholds in school chemistry. *International Journal of Science Education, 10*, 275–284.

Kennepohl, D. (2007). Using home-laboratory kits to teach general chemistry. *Chemistry Education Research and Practice, 8*, 337–346.

Kerr, J. F. (1963). *Practical work in school science: An account of an inquiry into the nature and purpose of practical work in school science teaching in England and Wales*. Leicester, UK: Leicester University Press.

Klahr, D. (2000). *Exploring science. The cognition and development of discovery processes.* Cambridge, MA: MIT press.

Kolioulis, D., & Tsaparlis, G. (2007). Eighth-grade chemistry, with emphasis on macroscopic-constructivist approach and the meaningful introduction of the concepts of molecule and atom – Teaching book and its preliminary evaluation by teachers (*in Greek*). *Proceedings of the 5th Greek Conference "Science education and new technologies in education", 2*, 680–689.

Krajcik, J., Mamlok, R., & Hug, B. (2001). Modern content and the enterprise of science: Science education in the 20th century. In L. Corno (Ed.), *Education across a century: The centennial volume* (pp. 205–238). Chicago, Illinois: National Society for the Study of Education (NSSE).

Lagowski, J. J. (1990). Entry-level science courses: The weak link. *Journal of Chemical Education, 67*, 541.

Laws, P. M. (1996). Undergraduate science education: A review of research. *Studies in Science Education, 28*, 1–85.

Lazarowitz, R., & Tamir, P. (1994). Research on using laboratory instruction in science. In D. L. Gabel (ed.), *Handbook of research on science teaching* (pp. 94–130). New York: Macmillan.

Leach, L. (1998). Teaching about the world of science in the laboratory: The influence of students' ideas. In J. Welllington (Ed.), *Practical work in school science: Which way now?* (pp. 52–68). New York:Routledge.

Lee, O., Eichinger, D. C., Anderson, C. W., & Berkheime, G. D. (1993). Changing middle school student's conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*, 249–270.

Levere, T. H. (2001). *Transforming matter – A history of chemistry from alchemy to the buckyball*. Baltimore and London: John Hopkins University Press.

Liapi, I., & Tsaparlis, G. (2007). Lower-secondary students perform themselves creative experiments on acids-bases that are connected to daily life – A first evaluation and comparison with conventional experiments (*in Greek*). *Proceedings of the 5th Greek Conference "Science education and new technologies in education", 2*, 725–734.

Lijnse, P. L., Licht, P., DeVos, W., & Warlo, A. J. (Eds.) (1990). *Relating macroscopic phenomena to microscopic particles*. Utrecht: CD-β Press.

Lunetta, V. N. (1998). The school science laboratory: Historical perspectives and centers for contemporary teaching. In P. Fensham (Ed.), *Developments and dilemmas in science education* (pp. 169–188). London: Falmer Press.

Lunetta V. N., Hofstein, A., & Clough, M (2007). Learning and teaching in the school science laboratory: An analysis of research, theory, and practice. In N. Lederman & S. Abel (Eds.), *Handbook of research on science education* (pp. 393–441). Mahwah, NJ: Lawrence Erlbaum.

Mc Donnell, C., O'Connor, C., & Seery, M. K. (2007). Developing practical chemistry skills by means of student-driven problem based learning mini-projects. *Chemistry Education Research and Practice, 8*, 130–139.

McRobbie, C. J., & Thomas, G. P. (2001). Changing the learning environment for enhanced explaining and understanding in a year 12 chemistry class. *Learning Environments Research, 3*, 209–227.

Meester, M. A. M., & Maskill, R. (1994). *Second year practical classes in undergraduate chemistry courses in England and Wales*. London: Royal Society of Chemistry.

Meheut, M., & Chomat, A. (1990). The bounds of children's atomimism: An attempt to make children build up a particulate model of matter. In P. L. Lijnse, P. Licht, W. DeVos, & A. J. Warlo (Eds.), *Relating macroscopic phenomena to microscopic particles* (pp. 266–282). Utrecht: CD-β Press.

Millar, R. (1990). Making sense: What use are particle ideas to children. In P. L. Lijnse, P. Licht, W. DeVos, & A. J. Warlo (Eds.), *Relating macroscopic phenomena to microscopic particles* (pp. 283–293). Utrecht: CD-β Press.

Millar, R., & Driver, R. (1987). Beyond processes. *Studies in Science Education, 14*, 33–62.

Monteyne, K., Mark S., & Cracolice, M. S. (2004). What's wrong with cookbooks (reply to Ault). *Journal of Chemical Education, 81*, 1559–1560.

National Research Council (1996). *National science education standards*. Washington DC: National Academy Press.

National Research Council (2000). *Inquiry and the national science education standards*. Washington DC: National Academy Press.

Neber, H., & Anton, M.-A. (2008). Promoting pre-experimental activities in high-school chemistry: Focusing on the role of students' epistemic questions. *International Journal of Science Education*, *309*(13), 1801–1822.

Neber, H., & Heumann-Ruprecht, D. (2006). Discovering learning by experimenting in chemistry. In I. Herztstell (Ed.), *From the Nurenberg funnel to the laptop* (pp. 289–298). Bonn, Germany: DVP.

Nelson, P. (2002). Teaching chemistry progressively: From substances, to atoms and molecules, to electrons and nuclei. *Chemistry Education Research and Practice, 3,* 215–228.

Niaz, M.. (1993). 'Progressive problemshifts' between different research programs in science education: A Lakatosian perspective. *Journal of Research in Science Teaching, 30,* 757–765.

Novak, J. D. (1998). *Learning, creating, and using knowledge*. Mahwah: Lawrence Erlbaum.

Novick, S., & Nussbaum, J. (1981). Pupils understanding of the nature of matter: A cross age study. *Science Education, 65,* 187–196.

Nurrenbern, S. C., & Robinson, W. R. (1997). Cooperative learning: A bibliography. *Journal of Chemical Education, 74,* 623–524.

Nussbaum, J. (1998). History and philosophy of science and the preparation for constructivist teaching: The case of particle theory. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Teaching science for understanding – A human constructivist view* (Ch. 2). London: Academic Press.

Parchmann, I., Gräsel, C., Baer, A., Nentwig, P., Demuth, R., Ralle, B., & the Chik Project Group. (2006). "Chemie in Kontext". A symbiotic implementation of a context-based teaching and learning approach. *International Journal of Science Education, 28,* 1041–1062.

Penner, D. E., Lehrer, R., & Schauble, L. (1998). From physical models to biomechanics: A design based modeling approach. *The Journal of the Learning Sciences, 7,* 429–449.

Pickering, M. (1987). What is going on in students' head in lab? *Journal of Chemical Education, 64,* 521–523.

Polman, J. L. (1999). *Designing project-based science: Connecting learners through guided inquiry*. New York: Teachers College Press.

Pomeroy, D. (1993). Implication of teacher beliefs about the nature of science: Comparisons of the beliefs of scientists, secondary teachers, and elementary teachers. *Science Education, 77*, 261–278.

Read, J. R., & Kable, S. H. (2007). Educational analysis of the first year chemistry experiment 'Thermodynamics Think-In': An ACELL experiment. *Chemistry Education Research and Practice, 8,* 255–273.

Reid, N., & Shah, I. (2007). The role of laboratory work in university chemistry. *Chemistry Education Research and Practice, 8,* 172–185.

Roth, W. M., & Roychoudhury, A. (1993). The development of science process skills in authentic contexts. *Journal of Research in Science Teaching, 30,* 127–152.

Rudd II, J. A., Greenbowe, T. J., Hand, B. M., & Legg, M. J. (2001). Using the science writing heuristic to move toward an inquiry-based laboratory curriculum: An example from physical equilibrium. *Journal of Chemical Education, 78,* 1680–1686.

Schwartz, A. T. (2006). Contextualised chemical education: The American experience. *International Journal of Science Education, 28,* 977–998.

Shilandd, T. W. (1999). Constructivism: The implications for laboratory work. *Journal of Chemical Education, 76,* 107–109.

Shitbley, Jr. I. A., & Zimmaro, D. M. (2002). The influence of collaborative learning on student attitudes and performance in an introductory chemistry laboratory. *Journal of Chemical Education, 79*, 745–748.

Stamovlasis, D., Dimos, A., & Tsaparlis G. (2006). A study of group interactions in learning lower secondary physics. *Journal of Research in Science Teaching, 43*, 556–576.

Stamovlasis, D., & Tsaparlis, G. (2001). Application of complexity theory to an information processing model in science education, *Nonlinear Dynamics in Psychology and Life Sciences, 5*, 267–286.

Sutton, A. (1985). *An introduction to assessment and evaluation processes and procedures*. Cardiff: University College.

Tobin, K. G. (1990). Research on science laboratory activities; in pursuit of better questions and answers to improve learning. *School Science and Mathematics, 90*, 403–418.

Tobin, K. G., & Capie, W. (1982). Relationships between formal reasoning ability, locus of control, academic engagement, and integrated process skill development. *Journal of Research in Science Teaching, 19*, 113–121.

Toomet, R, DePierro, E., & Garafalo, F. (2001). Helping students to make inferences about the atomic realm by delaying the presentation of atomic structure. *Chemistry Education Research and Practice, 2*, 129–144.

Trumper, R. (2003). The physics laboratory: A historical overview and future perspectives. *Science & Education, 12*, 645–670.

Tsai, C.-C. (1998). An analysis of scientific epistemological beliefs and learning orientations of Taiwanese eighth graders. *Science Education, 82*, 473–489.

Tsaparlis, G. (1989). What a single molecule does not look like – Two analogies and their effect on learning [Abstracts]. *American Chemical Society, 198*, 176 (Ched).

Tsaparlis, G. (1997). Atomic and molecular structure in chemical education – A critical analysis from various perspectives of science education. *Journal of Chemical Education, 74*, 922–925.

Tsaparlis, G. (1998) Dimensional analysis and predictive models in problem solving, *International Journal of Science Education, 20*, 335–350.

Tsaparlis, G., & Angelopoulos, V. (2000) A model of problem solving: its operation, validity and usefulness in the case of organic-synthesis problems. *Science Education, 84*, 131–153.

Tsaparlis, G., & Gorezi, M. (2005). Modification of a conventional expository physical chemistry laboratory to accommodate an inquiry/project-based component: Method and students' evaluation. *Canadian Journal of Science, Mathematics and Technology Education, 5*, 111–131.

Tsaparlis, G., & Gorezi, M. (2007). Addition of a project-based component to a conventional expository physical chemistry laboratory. *Journal of Chemical Education, 84*, 668–670.

Tsaparlis, G., & Zoller, U. (2003). Evaluation of higher *vs.* lower-order cognitive skills-type examinations in chemistry: Implications for university in-class assessment and examinations *University Chemistry Education, 7*(2), 50–57.

Vallarino, L. M., Polo, D. L., & Esperdy, K. (2001). Development of a research-oriented inorganic chemistry laboratory course. *Journal of Chemical Education, 78*, 228–231.

Vygotsky, L. (1962). *Thought and language*. Cambridge, MA: MIT Press.

Wallace, C. S., Tsoi, M. Y., Calkin, J., & Darely, M. (2003). Learning from inquiry-based laboratories in nonmajor biology: An interpretive study of the relationships among inquiry experience, epistemologies, and conceptual growth. *Journal of Research in Science Teaching, 40*, 986–1024.

Welzel, M. (1999). A study of factors determining the difficulty and interestingness of physics problems. Proceedings, *2nd International Conference of ESERA, Kiel, Germany, 2*, 369–371.

White, R., Gunstone, R., Elterman, E., Macdonald, I., McKittrick, B., Mills, D., & Mulhall, P. (1995). Students' perceptions of teaching and learning in first-year university physics. *Research in Science Education, 25*, 465–476.

Zimrot, R., & Ashkenazi, G. (2007). Interactive lecture demonstrations: A tool for exploring and enhancing conceptual change. *Chemistry Education Research and Practice, 8*, 197–211.

Zoller U. (1993). Are lecture and learning compatible? Maybe for LOCS unlikely for HOCS. *Journal of Chemical Education, 70*, 195–198.

Zoller, U., & Pushskin, D. (2007). Matching higher-order cognitive skills (HOCS) promotion goals with problem-based laboratory practice in a freshman organic chemistry course. *Chemistry Education Research and Practice, 8*, 155–171

Zoller, U., & Tsaparlis, G. (1997). Higher and lower-order cognitive skills: The case of chemistry. *Research in Science Education, 27*, 117–130.

Chapter 6
Linking the Macroscopic, Sub-microscopic and Symbolic Levels: The Case of Inorganic Qualitative Analysis

Kim Chwee Daniel Tan, Ngoh Khang Goh, Lian Sai Chia and David F. Treagust

Abstract Basic Grade 10 inorganic qualitative analysis in Singapore requires students to carry out procedures using chemicals, apparatus and appropriate techniques for which they record their observations and make inferences based on the observations. As students are assessed mainly on their written observations, they focus on getting the correct results and writing 'standard' observations. Thus, many students merely follow instructions given in the worksheet and seldom think about or understand the reactions involved especially in terms of what is occurring in these reactions at the sub-microscopic level. To respond to this situation, the authors first designed the Qualitative Analysis Diagnostic Instrument to identify students' understanding of the reactions involved in qualitative analysis. Secondly, the authors developed the Qualitative Analysis Teaching Package to help students learn qualitative analysis by facilitating their understanding of the sub-microscopic and symbolic level explanations of the macroscopic level experiences of the procedures and reactions involved, as well as the manipulative, observational and inferential skills and thinking processes required. The diagnostic instrument and teaching package are especially important with the imminent change from the current one-off national practical examination to school-based assessment in 2008 with the focus on manipulative, observational, analytical and planning skills.

Introduction

In Singapore, students start their formal chemical education, when they are 14–16 years old, in Grade 9. They will study chemistry for 2 years before they sit for the Singapore–Cambridge General Certificate of Education Ordinary Level (O-level) chemistry examinations at the end of Grade 10. The chemistry examinations consist of three papers, two theories and one practical. In their 2 years of

---

K.C. Daniel Tan (✉)
Nanyang Technological University, Nanyang Avenue Singapore
e-mail: daniel.tan@nie.edu.sg

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_7,

study, the students are taught the basic concepts of chemistry such as the kinetic theory of matter, atomic structure, chemical bonding, stoichiometry and chemical calculations, kinetics, energetics, oxidation–reduction, electrochemistry, as well as introductory inorganic and organic chemistry. They also acquire basic laboratory skills as they carry out simple experiments on rates of reaction and heat of reaction, as well as volumetric analysis and qualitative analysis in their laboratory sessions.

The topic, qualitative analysis, is an important component of the O-level chemistry course in Singapore. Questions on qualitative analysis can appear in both the theory and practical papers. In practical qualitative analysis, students are expected to carry out experiments on an unknown sample which can contain a single compound or a mixture of compounds, either in solution or the solid form. Based on their observations obtained in following the procedures given in the question paper, students have to make inferences about the nature and/or identity of unknown substances present. The ions and gases that the Grade 10 students are expected to identify are given in Table 6.1. Marks are awarded based on written reports that the students submit; the actual laboratory performance of the students during the practical examination is not assessed. In the theory papers, students can be given qualitative analysis data, in multiple choice or structured questions, to interpret and upon which to make inferences.

To carry out qualitative analysis experiments successfully, students need to be proficient in handling apparatus and reagents, know how to carry out the experiments and know what to look out for in the experiments. They also need to be able to record their observations properly and interpret their results appropriately. Thus, practical qualitative analysis involves manipulative, observational, recording and inferential skills. To understand the experiments that they carry out, the reactions that occur and the results that they obtain, students need to understand the sub-microscopic and symbolic level explanations of their macroscopic level experiences and apply concepts from other chemistry topics such as ‘Acids, Bases and Salts’, ‘Oxidation and Reduction’, ‘Reactivity of Metals’ and ‘Periodicity’. Consequently, students may experience cognitive overload (Johnstone & Wham, 1982) as a result of the considerable mental and physical demands of qualitative analysis practical work, making qualitative analysis a difficult topic to master.

Table 6.1 Ions and gases that students are expected to identify in O-level qualitative analysis

Cations	Anions	Gases
aluminium (Al^{3+})	carbonate ($CO_3{}^{2-}$)	ammonia (NH_3)
ammonium ($NH_4{}^{+}$)	chloride (Cl^{-}) [in solution]	carbon dioxide (CO_2)
calcium (Ca^{2+})	iodide (I^{-}) [in solution]	chlorine (Cl_2)
copper(II) (Cu^{2+})	nitrate ($NO_3{}^{-}$) [in solution]	hydrogen (H_2)
iron(II) (Fe^{2+})	sulfate (SO_4^{2-}) [in solution]	oxygen (O_2)
iron(III) (Fe^{3+})		sulfur dioxide (SO_2)
zinc (Zn^{2+})		

Student Difficulties with Qualitative Analysis

Many chemistry teachers in Singapore feel that their students do not understand what they are doing in the qualitative analysis practical sessions (Tan, 2000). Teachers frequently complain that students adopt a recipe-approach, cannot carry out the experimental procedures properly and do not understand the purpose of the experimental procedures. They find that students seldom think for themselves, and often resort to asking teachers for help in conducting the experiments, recording observations and making sense of their observations. Students, themselves, agreed that they had little idea on what they were doing during practical work, and were more concerned with getting the correct results than understanding the procedures and reactions involved (Tan, Goh, Chia, & Treagust, 2001). The students' lack of understanding has also been noted by the O-level examiners. For example, in the 1994 examination report (University of Cambridge Local Examinations Syndicate (UCLES, 1995)), the examiners stated that in the procedure which involved the addition of aqueous ammonia to the unknown samples, many students wasted time testing for ammonia gas which, not surprisingly, they were able to detect, while in the 1996 examination report (UCLES, 1997), the examiners highlighted that many students invented observations for several tests in which there should have been no reaction.

To address this problem, an initial step was to determine Singapore Grade 10 students' understanding of the procedures and reactions involved in qualitative analysis using a two-tier multiple choice diagnostic instrument (Treagust, 1995), the Qualitative Analysis Diagnostic Instrument (QADI; Tan, Goh, Chia, & Treagust, 2002). This instrument was administered to 915 Grade 10 students from 11 schools after being taught the topics 'Acids, Bases and Salts', 'Oxidation and Reduction', 'Periodicity' and 'Reactivity of Metals' and carrying out at least 10 qualitative analysis practical experiments. Consistent with the examination reports previously discussed, the results of this study showed that many students did not understand the interactions involved in qualitative analysis at the sub-microscopic level as well as the symbolic representations of these interactions. Two such examples, the formation of precipitates and complex salts and acid–salt reactions (Table 6.2), are now discussed in terms of the difficulties encountered.

Formation of Precipitates and Complex Salts

In O-level qualitative analysis, unknown cations are identified by reacting them with aqueous sodium hydroxide and/or aqueous ammonia. For example, zinc salt solutions react with aqueous sodium hydroxide to form a white precipitate, zinc hydroxide, which in turn will react with excess aqueous sodium hydroxide to form a colourless solution of sodium zincate, a complex salt. However, 25% of the 915 students thought that when sodium hydroxide solution was added to a solution of a zinc salt, a displacement reaction resulted leading to the formation of a precipitate

Table 6.2 Examples of students' alternative conceptions of reactions in qualitative analysis

Alternative conception	Choice combination	Percentage of students
Precipitates and complex salts		
1. A more reactive ion displaces a less reactive ion in a double decomposition/precipitation mixture.	Q1 (A3)	25
2. The precipitate dissolves in the excess reagent (instead of reacting with it) because		
a. more excess reagent means more space/volume for the precipitate to dissolve.	Q2 (A1)	29
b. no further reaction is seen except its disappearance and no new reagent is added.	Q2 (A2)	16
3. When acid is added to a mixture containing excess alkali and a complex salt (e.g. ammine, zincate or aluminate), it removes the solvent (alkali) which dissolved the precipitate in the first instance.	Q3 (A5)	18
Acid–salt/base reaction		
1. The insoluble base dissolves in the excess acid (instead of reacting with it) because no further reaction is seen except its disappearance and no new reagent is added.	Q4 (A3)	16
2. Carbonate ions cannot be identified if acid is added after the addition of barium nitrate(V).		
a. The acid must be added directly to the unknown.	Q11 (B4)	25
b. Addition of barium nitrate(V) invalidated the test for carbonates.	Q12 (B4)	20
c. The procedure is strictly a test for sulfate(VI).	Q11 (B3)	20

because the sodium ion was 'more reactive' than the zinc ion. This response showed that students did not understand that the precipitate was the result of a double decomposition reaction, and that in a displacement reaction, a more reactive element displaced the ion of a less reactive element, rather than a 'more reactive' ion displaced a 'less reactive' ion. The findings were similar to that by Butts and Smith (1987) who determined that the students could not relate the formation of a precipitate in a double decomposition reaction to the low solubility of the salt, and by Boo (1994) who found that students believed the driving force for a double decomposition reaction was the difference in reactivity between the metallic elements present in the compounds involved. The problem arose because students were seldom introduced to the sub-microscopic level representations of the formation of a precipitate – ions attracting each other and aggregating together to form larger masses which became visible at the macroscopic level. In the practical examinations, students were required to make observations at the macroscopic level and were generally not required to write equations for the reactions involved, so the symbolic representation of the formation of the precipitate also was not emphasized. Nevertheless, the ionic equation describing the precipitation reaction [for example, $Zn^{2+}(aq) + 2OH^{-}(aq) \rightarrow Zn(OH)_2(s)$] would have given students an idea that the zinc ions and hydroxide ions came together to form a solid, zinc hydroxide. Thus, it was not surprising that the results of the administration of the QADI showed that students did not understand the formation of precipitates.

In qualitative analysis laboratory sessions in Singapore, students were taught the reactions of amphoteric oxides/hydroxides with excess sodium hydroxide to form soluble complex salts but were not required to write chemical equations for the reactions in the examinations. By not writing these equations, students do not have the opportunity to relate the solutions and solids at a macroscopic level with their sub-microscopic ions and their interactions represented in symbolic form. Only 19% of the students could explain the disappearance of the zinc hydroxide precipitate when excess aqueous sodium hydroxide was added to the mixture. There were students (26%) who indicated that the precipitate ‘dissolved’ in the excess alkali but chose the correct reason that a reaction occurred and a new soluble substance was formed. This response might not be a problem as the students knew the reason, so only the term ‘dissolving’ needed to be clarified. However, it was problematic if students thought that the precipitate dissolved because there was more ‘solvent’ (excess alkali) for it to dissolve in (29%), or because no further reaction was seen except the disappearance of the precipitate and no new reagent was added (16%). The fact that the precipitate was formed when the ‘solvent’ was added in the first instance seemed to be overlooked by the students. Ribeiro, Pereira, and Maskill (1990) also reported that if students did not see a new substance being formed – a macroscopic change – they tended not to refer to the change as a reaction occurring at a sub-microscopic level. Unfortunately, this problem was further compounded by students being taught to write ‘white precipitate dissolves in excess aqueous sodium hydroxide to give a colourless solution’, a ‘standard’ answer required in the examinations to describe the disappearance of the precipitate. Thus, if teachers did not emphasize the chemical species involved by writing chemical and ionic equations, it would not come as a surprise that the students thought the precipitate merely dissolved in the excess alkali at the macroscopic level.

Acid–Salt Reactions

Students usually identify the existence of anions such as carbonate, iodide and sulfate(VI) by adding a barium/silver(I)/lead(II) solution to the unknown, followed by a dilute acid or vice-versa in qualitative analysis practical work sessions and examinations. Many students had difficulty understanding the roles of the barium/silver(I)/lead(II) solution and the dilute acid in the tests for anions. For example, 20% believed that the addition of aqueous barium nitrate(V) followed by dilute nitric(V) acid was to test for sulfate(VI) only. Another 25% believed that to test for a carbonate, acid had to be added directly to the unknown sample, while 20% believed that the addition of barium nitrate(V) invalidated the test for carbonates. When the students were asked the purpose of adding dilute nitric(V) acid following the addition of silver nitrate(V) solution (in one question) and lead(II) nitrate(V; in another question) to the unknown solutions, 22% and 35%, respectively, indicated that it was to allow the silver nitrate(V) and lead(II) nitrate(V) to ‘react properly’ with the unknown substances. However, these students were unable to explain what ‘react properly’ meant. These responses showed that students did not understand that the function of the barium/silver/lead(II) solutions was to form insoluble barium/silver/lead(II) salts and the role of the dilute acid was to liberate carbon dioxide or sulfur dioxide, which could then be identified, if carbonate and sulfate(IV) was present. The sub-microscopic level representation of the formation of the insoluble barium/silver/lead(II) salts is similar to that in the tests for cations. Consequently, if students understand the formation of precipitates in the test for cations, they should also be able to understand that a similar process is also involved in the formation of precipitates in the test for anions. This understanding could also help students realize that reactions occurring in chemistry are not ‘random’ but that similar types of reactions are actually occurring with different chemical entities.

The Qualitative Teaching Package

The second step to address the problems encountered in students’ learning qualitative analysis was to develop a teaching package. In Singapore, teachers normally begin teaching qualitative analysis by reviewing the reactions involved and demonstrating some procedures that the students need to carry out. Laboratory sessions follow where students conduct a series of tests for the various cations, anions, gases, oxidising and reducing agents using commercially available workbooks or teacher-prepared worksheets. After they are familiar with the tests, students are given past years’ examination questions to determine the unknown ions (Table 6.1) or to deduce the properties of the unknown substances to prepare them for the practical examinations. Students sit for a one-off national end-of-year practical examination in Grade 10 and are assessed solely on their written reports, so students concentrate on carrying out the procedures given and getting the ‘correct’ observations because their observations account for most of the marks. This resulted in drill and practice in qualitative analysis practical work in schools (Goh, Toh, & Chia, 1987) – it demanded little cognitive effort but paid off handsomely in terms of results.

Nevertheless, the existence of the students’ difficulties showed that the usual way of teaching qualitative analysis did not help students understand the procedures and reactions involved in qualitative analysis. Additional indications were obtained from interviews with 51 students from three schools involved in the study to determine their perceptions of their learning of QA (Tan et al., 2001). Twenty-six students admitted that they frequently did not have any idea about what they were doing during the QA practical sessions. To illustrate this point, 14 students mentioned that when they had to test for a gas during practical sessions, they wasted time testing for all the gases that were in the syllabus and usually used up all the gas evolved before they could complete all the tests. They did not seem to realize that the procedures and the reagents used could indicate which gases might be evolved during the process.

Fortunately, changes in the assessment system are forthcoming. From 2008 onwards, practical assessment will be school-based, and students will be evaluated on their manipulative, observational, analytical and planning skills (Ministry of Education, 2006). Thus, students are no longer assessed mainly on the ‘correct’ observations, but have to show competency in carrying out procedures, analysing results and planning experiments – the normal qualitative analysis laboratory instruction will not be adequate in preparing students for the new school-based practical assessment system. In response to the difficulties that students have learning qualitative analysis and the impending change in practical assessment, the authors developed an instructional package on qualitative analysis, the Qualitative Analysis Teaching Package (QATP; Tan, 2000; Tan, Goh, Chia, & Treagust, 2004) to help students learn qualitative analysis in a more comprehensive manner. The aims of the package are to allow students to: (1) be exposed to the macroscopic, sub-microscopic and symbolic representations of the main reactions involved in qualitative analysis; (2) gain tacit knowledge of reagents, apparatus and reactions; (3) gain proficiency in manipulative, observational and inferential skills; (4) learn the thinking/reasoning required in QA; and (5) apply what they have learnt to plan, execute and evaluate experiments to identify unknown samples. The instructional package is divided into four main sections, ‘Cations’, ‘Gases’, ‘Anions’ and ‘Strategies’. The authors considered the identification of cations to be the easiest to start with as it involved mainly double decomposition and precipitation, while the identification of anions was the most difficult because it also involved the identification of gases. Thus, the section on cations preceded the section on gases followed by the section on anions. The activities in each section were generally in the following sequence ‘Experience’, ‘Exercise’, ‘Applications’ (Woolnough & Allsop, 1985) and ‘Strategies’ (Pintrich, Marx, & Boyle, 1993; Volet, 1991). Students experienced a certain chemical phenomenon – the macroscopic level – and learned the theory and reactions – at the sub-microscopic and symbolic levels – behind it. Subsequently, students proceeded to practise the manipulative skills required to carry out the procedures involved, learn what to observe, how to record their observations at both the macroscopic and symbolic levels and how to plan their own experiments. They also were introduced to the thinking or strategies involved in doing qualitative analysis experiments.

Experiencing the Phenomena

The section on tests for cations is used to illustrate the QATP. Students need to have tacit knowledge of the phenomena involved in qualitative analysis, reagents and apparatus, and to construct explanations of the phenomena at the sub-microscopic level and to write equations to describe them. To help students understand precipitate formation, they are instructed to compare the behaviour of two solutions, sodium chloride and iron(III) chloride when aqueous sodium hydroxide is added to the solutions (Fig. 6.1). The students will observe that there is no visible reaction with the sodium chloride solution, but a brown precipitate will be formed in the

Procedure	What you see
1. Add aqueous sodium chloride into a test tube until it reaches a height of 1 cm. Add two drops of aqueous sodium hydroxide and shake the mixture. 2. Add aqueous iron(III) chloride into a test tube until it reaches a height of 1 cm. Add two drops of aqueous sodium hydroxide and shake the mixture.	

1. Explain the differences in what happened above.
2. Compare your answer with your partner or another pair/group and try to reconcile differences (if any). Write down the agreed explanations if it is different from (1).
3. After listening to the explanation given by your teacher, in your own words, explain what is meant by: (you may discuss with your classmates)
   a. double decomposition reaction.
   b. precipitation reaction.
   c. sodium chloride (common salt) is soluble in water.
   d. iron(III) hydroxide is insoluble.

Fig. 6.1 Addition of aqueous sodium hydroxide to aqueous sodium chloride and aqueous iron(III) chloride

test tube containing the iron(III) chloride solution. They are required to explain the observations, and discuss and compare their ideas with their classmates.

The students also listen to the teacher’s explanations carefully, compare them with their own ideas and try to resolve any differences or any areas that they do not understand using a similar procedure described by Driver and Oldham (1986). The key concepts involved in this case, solubility and precipitation, are further clarified using computer animation sequences to provide students with concrete sub-microscopic level representations of chemical structures and reactions (Garnett, Garnett, & Hackling, 1995; Harrison & Treagust, 1998). Dechsri, Jones, and Heikkinen (1997) noted that images of representations at the sub-microscopic level were more easily recalled than words and could act as an ‘easily recalled conceptual peg for abstract concepts’ (p. 892). When students see the animation of the particles of a soluble salt being bombarded by water molecules and the particles leaving, surrounded by the water molecules, leading to the ‘disintegration’ of the salt, they should realize that the salt ‘disappears’ because salt grains have been broken down to the individual ions that are too tiny to be seen. In these animations, students also see the behaviour of an insoluble salt in water where the water molecules cannot ‘pull’ the particles away from each other. Thus, the salt grains are still large enough to be seen.

At the macroscopic level, students can also be shown a piece of iron ‘disappearing’ in dilute hydrochloric acid and asked to comment on the statement that the hydrochloric acid ‘dissolves’ the iron. This task highlights the difference in the use of the word ‘dissolve’ in science and in everyday life. The students need to be aware that iron disappears in hydrochloric acid because at the sub-microscopic level: (1) there is a redox reaction between the iron atoms and the hydrogen ions forming iron(II) ions and hydrogen gas; (2) the iron(II) ions are solvated by the water molecules; and (3) the iron(II) ions do not form an insoluble compound with the chloride ions. The intention of this activity is that students are able to picture iron(II) ions moving about in the solution rather than iron atoms being dispersed in the solution. These observations may help students realize that there is a difference when a substance merely dissolves in a liquid and when it reacts with the liquid to form soluble substances. Teachers should point out that if a substance disappears without any visible reaction, a reaction still could have occurred. For example, the disappearance of solid sodium chloride in water and solid calcium oxide in dilute hydrochloric acid may look similar at the macroscopic level, but the processes involved at the sub-microscopic level are different.

Once the concept of solubility is understood, students look at animations that show two solutions being mixed resulting in the exchange of ions and formation of an insoluble compound (see the screen captures in Figs. 6.2, 6.3 and 6.4). Students generally do not consider how precipitates are formed, so the animation showing how the ions (at the sub-microscopic level) attract each other and aggregate to form a precipitate (at the macroscopic level) will help them to understand the interactions of the ions involved.

The next step is to write the chemical equation and derive the ionic equation which more adequately describes the precipitation process. Thus, students will be

Fig. 6.2 Screen capture showing the solute particles in the two solutions (without the water molecules). Reproduced with permission from Intellilife Inc. Pte. Ltd

Fig. 6.3 Screen capture showing the formation of an insoluble salt. Reproduced with permission from Intellilife Inc. Pte. Ltd

exposed to the three levels of representation when they observe a precipitation reaction – the results from the addition of the reagents (macroscopic level), the computer animation (sub-microscopic level) and the relevant chemical and ionic equations (symbolic level) – to help them understand the processes better.

Fig. 6.4 Screen capture showing the precipitate settling to the bottom of the beaker. Reproduced with permission from Intellilife Inc. Pte. Ltd

Understanding the Procedures

The manipulative skills needed to test for cations are outlined in Fig. 6.5. Students are encouraged to carry out procedures as many times as necessary until they are proficient in them. Students do face problems if the way they carry out procedures is incorrect. For example, by adding too much aqueous sodium hydroxide at one time to a test tube containing a solution of a zinc salt, they may not see the formation of a precipitate, thus missing out on a vital piece of information. As Hodson (1990) argues, practical work is not just for students to acquire laboratory skills, students need to master certain skills and concepts in order to carry out the practical work successfully; this means having an understanding of the relationship between the three levels of representation involved in chemical reactions to make sense of what they doing in the laboratory.

In science laboratory sessions, students frequently do not think for themselves and seem unaware of what they should be doing (Berry, Mulhall, Gunstone, & Loughran, 1999) even though teachers assume their students do know what to do during experiments, and thus, seldom emphasize or make explicit the purpose of and the theory behind the procedures (Tasker & Freyberg, 1985). To ensure that they understand the rationale behind the procedures, in the instructional package for qualitative analysis, students are asked questions on why certain procedures have to be carried out in a certain way, for example, why they are supposed to add only two drops of aqueous sodium hydroxide initially in the test for cations. A related procedure which also causes problems for students is clarified by explaining that adding

1. **Aims**

   You will learn to:

   a. Put the appropriate amount of the zinc solution to be tested into a test tube.
   b. Add a small amount of aqueous sodium hydroxide to the zinc solution.
   c. Add aqueous sodium hydroxide until it is in excess.
   d. Shake the mixture after each addition of aqueous sodium hydroxide.

2. **Skills to be practised**

   a. Solution to be tested
      When you add the zinc solution into a test tube, you should add till it just covers the hemisphere at the bottom of the test tube. Why?
   b. A small amount of reagent
      When you add a small amount of aqueous sodium hydroxide, you should add about two drops and shake the mixture thoroughly (by shaking the test tube or using a glass rod to stir). Why?
   c. Excess reagent
      When you add aqueous sodium hydroxide, you should add 1 cm height portions at a time, shaking the mixture thoroughly each time until the mixture reaches about 2 cm from the top of the test tube. If there is a need to, pour away 3/4 of the content of the test tube and continue adding as described.

Fig. 6.5 Skills required for the testing of cations a dilute acid such as hydrochloric acid to an insoluble solid such as zinc oxide, and using aqueous sodium hydroxide to test for the cation present in the resulting solution, excess acid may be present so they will not get a white precipitate if they just add two drops of the alkali. In this case, teachers can use a sub-microscopic level representation to show that the excess hydrogen ions (hydroxonium ion is not taught at the O-level) are more likely to react with the hydroxide ions from the alkali than the zinc ions, or if zinc hydroxide is formed, the excess acid will neutralize it to form soluble zinc chloride. In this situation, students need to know the reason for adding the alkali carefully to ensure that all the excess acid is neutralized and monitoring the process with litmus paper before ascertaining that no precipitate is formed. Students need to know the rationale for the procedures so that they will take care to adhere to the procedures, as well as link them with the knowledge about the interactions of the ions involved in the reactions that they learn in class.

Applying the Knowledge and Skills

After students learn the reactions and rationale of the procedures involved, and are proficient in carrying out the required procedures without any instructions, they are given unknown samples to determine the cations present. Thus, in planning experiments, students need to apply what they have learned and this is intended to increase their confidence in the knowledge and skills acquired. This goal is consistent with that of Schauble, Klopfer, and Raghavan (1991) who showed that when students become aware that experiments require analytic or extended reasoning, they start to try to understand the relevant concepts involved in experiments instead of merely focussing on results. The aim of the application activities in the instructional package is to provide such opportunities in contrast to the normal teaching of qualitative analysis in Singapore schools where students have little opportunity for planning experiments because these are not required in the one-off practical examinations.

Thinking Required for Qualitative Analysis

Research has shown that students tend not to see the relationship between practical work (the macroscopic level) and theory (at the sub-microscopic and symbolic levels), but without theory to guide their experiments, it is unlikely that students will know what to think about and what to take note of in the experiments (Hodson, 1992). Normal qualitative analysis practical work and examinations in Singapore involve following given procedures and observing what happens, so in order to understand what happens at the sub-microscopic level, students need to be able to determine the objectives of the procedure, what reactions can occur and hence what precautions to take and what results to expect; they need to learn to engage in the required specific thinking processes (Swartz, 1991). Thus, teachers need to model the thinking processes required (Pintrich et al., 1993; Volet, 1991) by showing their students how they analyse a worksheet or practical examination paper and how the analysis guides the execution of the procedures. The students should then practise analysing worksheets or past years' examination questions in a similar way to familiarize themselves with the thinking processes and to allow reflection on their thinking. These activities should help students to see the link between theory and practice, and guide them in their qualitative analysis practical work.

Conclusion

The procedures at the macroscopic level and reactions at the sub-microscopic and symbolic levels involved in qualitative analysis are fundamentally important for students to understand the chemical reactions in qualitative analysis practical work. However, to prepare students for the examinations, the usual way of doing qualitative analysis mainly requires students to follow instructions and write the required observations, so the chemical reactions involved are not emphasized in textbooks and workbooks, and by teachers. Consequently, students generally have difficulties linking the procedures that they execute with the results obtained and the theory learned. The challenge for teachers is to help students experience the reactions (at the macroscopic level), introduce the relevant reactions with chemical equations (at the symbolic level) and use analogy and/or multimedia animations to describe what happens in the reactions (at the sub-microscopic level) so that students are able to construct explanations of the phenomena. Teachers also need to facilitate students' acquisition of the manipulative, observational and inferential skills and thinking processes required in qualitative analysis, and students should have opportunities to apply what they have learnt to plan, execute and evaluate experiments to identify unknown samples. Thus, better ways of conducting qualitative analysis practical work are required and using the QATP may be a step in this direction, especially with the imminent change over to school-based practical assessment in Singapore in 2008 with the focus on manipulative, observational, analytical and planning skills.

References

Berry, A., Mulhall, P., Gunstone, R., & Loughran, J. (1999). Helping students learn from laboratory work. *Australian Science Teachers' Journal, 45*(1), 27–31.

Boo, H. K. (1994). *A-level chemistry students' conceptions and understandings of the nature of chemical reactions and approaches to learning of chemistry content*. Unpublished Ph.D. thesis, University of London, London.

Butts, B., & Smith, R. (1987). HSC chemistry students' understanding of the structure and properties of molecular and ionic compounds. *Research in Science Education, 17*, 192–201.

Dechsri, P., Jones, L. L., & Heikkinen, H. W. (1997). Effect of a laboratory manual design incorporating visual information-processing aids on student learning and attitudes. *Journal of Research in Science Teaching, 34*(9), 891–904.

Driver, R., & Oldham, V. (1986). A constructivist approach to curriculum development in science. *Studies in Science Education, 13*, 105–122.

Garnett, P. J., Garnett, P. J., & Hackling, M. W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education, 25*, 69–95.

Goh, N. K., Toh, K. A., & Chia, L. S. (1987). *The effect of modified laboratory instruction on students' achievement in chemistry practicals*. Research report, Institute of Education, Singapore.

Harrison, A. G. & Treagust, D. F. (1998). Modelling in science lessons: Are there better ways to learn with models? *School Science and Mathematics, 98*(8), 420–429.

Hodson, D. (1990). A critical look at practical work in school science. *School Science Review, 70*(256), 33–40.

Hodson, D. (1992). Redefining and reorienting practical work in school science. *School Science Review, 73*(264), 65–78.

Johnstone, A. H. & Wham, A. J. B. (1982). The demands of practical work. *Education in Chemistry, 19*, 71–73.

Ministry of Education (2006). *Chemistry: GCE Ordinary Level (Syllabus 5072).* Singapore: Author. Retrieved May 18, 2007, from http://www.seab.gov.sg/SEAB/oLevel/syllabus/2008_GCE_O_Level_Syllabuses/5072_2008.pdf.

Pintrich, P. J., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*, 167–200.

Ribeiro M. G. T. C., Pereira, D. J. V. C., & Maskill, R. (1990). Reaction and spontaneity: the influence of meaning from everyday language on fourth year undergraduates' interpretations of some simple chemical phenomena. *International Journal of Science Education, 12*(4),391–401.

Schauble, L., Klopfer, L. E., & Raghavan, K. (1991). Students' transition from an engineering model to a science model of experimentation. *Journal of Research in Science Teaching, 28*(9), 859–882.

Swartz, R. J. (1991). Infusing the teaching of critical thinking into content instruction. In Costa, L. A. (Ed.), *Developing minds: A resource book for teaching thinking*. (Vol. 1, pp. 177–184). Alexandria, VA: Association for Supervision and Curriculum Development.

Tan, K. C. D. (2000). *Development and application of a diagnostic instrument to evaluate secondary students' conceptions of qualitative analysis.* Unpublished Ph.D. thesis, Curtin University of Technology.

Tan, K. C. D., Goh, N. K., Chia, L. S., & Treagust, D. F. (2001). Secondary students' perceptions about learning qualitative analysis in inorganic chemistry. *Research in Science & Technological Education, 19*(2), 223–234.

Tan, K. C. D., Goh, N. K., Chia, L. S., & Treagust, D. F. (2002). Development and application of a two-tier multiple choice diagnostic instrument to assess high school students' understanding of inorganic chemistry qualitative analysis. *Journal of Research in Science Teaching, 39*(4), 283–301.

Tan, K. C. D., Goh, N. K., Chia, L. S., & Treagust, D. F. (2004). Qualitative analysis practical work. *School Science Review, 85*(313), 97–102.

Tasker, R. & Freyberg, P. (1985). Facing the mismatches in the classroom. In Osborne, R. & Freyberg, P. (Eds.), *Learning in science: The implications of children's science* (pp. 66–80). Auckland, London: Heinemann.

Treagust, D. F. (1995). Diagnostic assessment of students' science knowledge. In S. M. Glynn & R. Duit (Eds.), *Learning science in the schools: Research reforming practice* (pp. 327–346). Mahwah, New Jersey: Lawrence Erlbaum Associates.

University of Cambridge Local Examinations Syndicate. (1995). *Chemistry: Report on the November 1994 examinations*. Cambridge: Author.

University of Cambridge Local Examinations Syndicate. (1997). *Chemistry: Report on the November 1996 examinations*. Cambridge: Author.

Volet, S. E. (1991). Modelling and coaching of relevant metacognitive strategies for enhancing university students' learning. *Learning and Instruction, 1*, 319–336.

Woolnough, B. & Allsop, T. (1985). *Practical work in science*. Cambridge: Cambridge University Press.

Chapter 7

The Efficacy of an Alternative Instructional Programme Designed to Enhance Secondary Students' Competence in the Triplet Relationship

David F. Treagust and A.L. Chandrasegaran

Abstract Research has consistently shown that secondary school students have conceptual difficulties transferring between macroscopic, submicroscopic and symbolic representations in chemistry. In this chapter, we describe how students responded to a 15-item two-tier multiple choice diagnostic instrument that analysed their understanding of seven types of chemical reactions using macroscopic, submicroscopic and symbolic representations after they had been taught a special alternative programme to make these three representations more overt. The research has shown that by placing particular emphasis on the triplet relationship of macroscopic, submicroscopic and symbolic representations in chemistry, it is possible for students to achieve more meaningful learning of chemical representations. Suggestions are made for how such improved learning can be accommodated in normal classrooms, as compared to research-oriented classrooms.

Introduction

Studies in science education indicate that secondary school students have limited understanding of the triplet relationship involving *macroscopic*, *submicroscopic* and *symbolic* representations in chemistry (Andersson, 1986; Ben-Zvi, Eylon, & Silberstein, 1986, 1987, 1988; Gabel, 1998, 1999; Gabel, Samuel, & Hunn, 1987; Johnstone, 1993; Nakhleh & Krajcik, 1994). Even students in a beginning undergraduate course in chemistry have been found to experience difficulty understanding multiple levels of representation associated with chemical concepts (Bodner, 1991). In an attempt to facilitate students' conceptual understanding of multiple levels of representation, several studies have been conducted over the years (Ben-Zvi, Eylon, & Silberstein, 1986; Gabel, 1998; Keig & Rubba, 1993; Kozma & Russell, 1997; Treagust, Chittleborough, & Mamiala, 2003). In this chapter we discuss the results of a study designed to diagnose the competence of Grade 9 students as a consequence of an instructional programme structured to provide more meaningful understanding of

---

D.F. Treagust (✉)
Curtin University of Technology, Perth, WA 6845, Australia
e-mail: d.f.treagust@curtin_edu.au

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_8,

the changes that take place during chemical reactions using the triplet relationship between macroscopic, submicroscopic and symbolic representations.

Theoretical Framework

The study that was undertaken was based on a constructivist approach grounded in the fundamental tenet that considers what a learner already knows to be a major factor in determining the outcomes of learning and provides the learner with opportunities to develop new understandings with the teacher acting as a facilitator of learning rather than as a transmitter of knowledge (Ausubel, 1968). Chemistry learning is generally considered difficult for students due to the complex and abstract nature of the subject (Ben-Zvi, Eylon, & Silberstein, 1987, 1988; Gabel, 1998, 1999; Johnstone, 1991, 1993; Nakhleh, 1992; Treagust & Chittleborough, 2001).

It is not surprising then that students hold particular idiosyncratic views about scientific phenomena and concepts that they bring with them to science lessons. These preinstructional conceptions about the behaviour of matter held by students that often tend to differ from the views of the scientific community are the result of several factors, such as their sensory experiences and the influence of their cultural background, peers, mass media as well as classroom instruction (Duit & Treagust, 1995). It is likely that students are satisfied with their own conceptions as a result of viewing material that is presented by their teachers or textbooks "through the lenses of their preinstructional conceptions" (Duit & Treagust, 1995; p. 47). From the cognitive point of view, the preinstructional conceptions held by students and those of the scientific community are constituted in different qualitative frameworks (Duit & Treagust, 1998). These student conceptions tend to be deeply rooted as coherent but mistaken conceptual structures that are resistant to change and so when the new concepts do not make sense to them, students tend to adhere firmly to their own views. Such reluctance by students to change their views often presents a serious barrier to effective teaching (Tytler, 2002). Efforts to identify students' preinstructional conceptions about particular concepts can provide useful feedback to teachers in the formulation of appropriate instructional strategies that can be used to challenge students' understandings in order to help them develop more scientifically acceptable views about those concepts.

The three representations that are referred to in this study are: (1) macroscopic representations that describe the bulk observable properties of matter, for example, heat energy, pH and colour changes, and the formation of gases and precipitates, (2) submicroscopic (or molecular) representations that provide explanations at the particulate level in which matter is described as being composed of atoms, molecules and ions, and (3) symbolic (or iconic) representations that involve the use of chemical symbols, formulas and equations, as well as molecular structure drawings, models and computer simulations that symbolise matter (Andersson, 1986; Boo, 1998; Johnstone, 1991, 1993; Nakhleh & Krajcik, 1994; Treagust & Chittleborough, 2001).

In order to achieve deep understanding of the changes that occur during chemical reactions, students should be able to relate the observed macroscopic changes to the rearrangement of particles that occurs at the submicroscopic level of representation and to the appropriate chemical equation at the symbolic level of representation. Studies, however, have shown that students generally construct most of their understanding in chemistry using macroscopic representations but are not very successful in building understandings that relate the macroscopic representations to submicroscopic and symbolic representations (Nakhleh & Krajcik, 1994). This trend in students' construction of knowledge could be attributed to their prior knowledge of chemistry that is entrenched mainly at the macroscopic level as a result of their everyday experiences. Also, secondary students are often not able to translate one given representation into another due to their limited conceptual knowledge and poor visual–spatial ability (Keig & Rubba, 1993; Seddon & Eniaiyeju, 1986). Additionally, classroom instruction that is often restricted by syllabus and time constraints almost entirely ignores the necessity to stress the relationship between the three levels of representation, further contributing to students' main preoccupation with macroscopic representations.

To be able to explain chemical reactions, students will have to develop mental models of the submicroscopic particles of the substances that undergo rearrangement to produce the observed changes. However, students have difficulty in understanding submicroscopic and symbolic representations as these representations are abstract and cannot be directly experienced (Ben-Zvi, Eylon, & Silberstein, 1986, 1988; Griffiths & Preston, 1992). As a result, how well students understand chemistry depends on how proficient they are in "making sense of the invisible and the untouchable" (Kozma & Russell, 1997; p. 949).

As for symbolic representations involving chemical equations, students often regard these as a means of representing a balanced number of atoms of each type, not as a representation of a chemical reaction at the particulate level (Ben-Zvi, Eylon, & Silberstein, 1987; Garnett, Garnett, & Hackling, 1995; Nurrenbern & Pickering, 1987). The problem is exacerbated by teachers and textbook writers who, in their explanations, overlook the intrinsic difficulties that students are confronted with when dealing with the particulate model. Besides the abstract concepts of atoms and molecules, students have to understand the several levels of representation that are communicated by symbols. An example is a textbook illustration for the chemical reaction $2H_2(g)+O_2(g) \rightarrow 2H_2O(g)$ that represents volumes of each of the gases H_2, O_2 and H_2O, by single molecules (Ben-Zvi, Eylon, & Silberstein, 1987).

Students' success in balancing chemical equations usually involves applying a learned set of rules. Subscripts in formulas are treated just as numbers that are used in balancing chemical equations and do not represent specific atomic groupings. Coefficients that appear in front of chemical formulas are simply numbers that are used to mechanically balance chemical equations, and do not represent the relative numbers of species reacting or being produced in chemical reactions. Such a mechanistic approach to balancing chemical equations results in students completely missing the dynamic and interactive significance of the chemical reaction with regard to the particles involved.

When students do make an attempt to relate between the three levels of representation, several unexpected trends in their reasoning are revealed. In the majority of explanations given by students about chemical reactions in a review undertaken by Andersson (1986), there was a clear extrapolation of physical attributes and changes from the macroscopic world to the particle or submicroscopic one. So, when wood burns, wood molecules are also said to burn. If metallic copper is bright reddish-brown, atoms of copper are also imagined to be reddish-brown in colour (Ben-Zvi, Eylon, & Silberstein, 1986). One reason for such extrapolation of physical attributes of substances to the particulate level is the tendency of students to assume that the atoms, ions and molecules in a substance are very small portions of the continuous substance.

Background and Purpose of the Study

In the first 2 years of secondary school in Singapore (Grades 7 and 8), all students follow a general science course. In the last 2 years of secondary school (Grades 9 and 10), students generally continue with general science or study either two or three ‘pure’ science subjects selected from physics, chemistry and biology. At the end of 4 years, most students sit for the University of Cambridge Local Examinations Syndicate (UCLES) Ordinary Level (‘O’- Level) Examination.

The prescribed chemistry curriculum includes several chemical reactions that students encounter in their studies in Grades 9 and 10. The chemical reactions are introduced in the regular programme of instruction when discussing several topics like acids, bases and salts, metal reactivity series, inorganic qualitative analysis, oxidation and reduction and electrochemistry. Students have to know the chemical equations for the various reactions but are not required to explain the changes that occur at the particulate level. As a result of their limited understanding, students generally memorise the chemical equations and regurgitate them in tests and examinations (Tan, Goh, Chia, & Treagust, 2002). Students’ limited understanding of chemical reactions and equations is also reflected in examination reports by the UCLES that are disseminated after the examination results are released each year.

In view of these reasons as well as the reports in the research literature that attest to difficulties associated with the use of multiple levels of representation, an alternative programme of instruction was developed with the aim of facilitating Grade 9 students’ to explain chemical reactions using chemical symbols, formulas and equations as well as atoms, molecules and ions, thereby engendering more meaningful understanding of the changes that occur during chemical reactions. Hence, the purpose of this study to evaluate the efficacy of the alternative instructional programme that was developed was guided by two research questions: (1) How competent are Grade 9 students in the use of the triplet relationship involving macroscopic, submicroscopic and symbolic representations when describing and explaining chemical reactions? (2) To what extent is the alternative programme of instruction successful in enhancing students’ ability to describe and explain some frequently encountered chemical reactions making use of the triplet relationship?

Methodology

Research Design and Sample

The research methodology used was a mixed quantitative and qualitative case study (Anderson, 2004). The study was part of a wider action research study that involved the development and validation of a two-tier multiple choice diagnostic instrument (the *Representational Systems and Chemical Reactions Diagnostic Instrument, RSCRDI)* to evaluate secondary students' competencies in describing and explaining chemical reactions using multiple levels of representation (Chandrasegaran, Treagust, & Mocerino, 2007). A purposeful convenience sample (Merriam, 1998) of 65 Grade 9 students from two classes (one each of high and average achieving classes) that were taught by the first author was involved in the implementation of the alternative instructional programme. At the end of the instruction, the efficacy of the alternative instructional programme in facilitating students' competence in the use of the triplet relationship was evaluated by administering the RSCRDI to the 65 students. As a comparison, the RSCRDI was also administered to another sample of 76 students from two other high achieving classes that were taught by the second author's teaching colleagues using the regular programme of instruction that did not place particular emphasis on the triplet relationship.

The high achieving classes had four 45-minute periods of chemistry instruction per week, of which two periods each week were laboratory lessons that were geared specifically to the practical examination. These laboratory lessons had limited relevance to the topics that were covered during classroom instruction. The average achieving classes had an additional period each week for classroom instruction. The period of the instruction in Grade 9 was over nine months. Allowing for time taken up by tests, examinations and school and public holidays, the high and average achieving classes received a total of about 96 and 120 hours, respectively of chemistry instruction during the nine months.

Chemical Reactions Included in the Study

Seven chemical reactions were identified from the chemistry syllabus. These chemical reactions were selected because they were frequently encountered during the 2-year chemistry course and based on their importance in understanding concepts associated with three topics, namely, acids, bases and salts, metal reactivity series and inorganic chemistry qualitative analysis. The seven types of chemical reactions were: combustion of reactive metals in air, chemical reactions between dilute acids and reactive metals, neutralisation reactions between strong acids and strong alkalis, neutralisation reactions between dilute acids and metal oxides, chemical reactions between dilute acids and metal carbonates, ionic precipitation reactions and metal ion displacement reactions. Although two of the chemical reactions involved oxidation and reduction, it was decided not to include the concept of redox in this study as students had only recently been introduced to ion-electron equations and oxidation states. Furthermore, redox reactions were to be covered more extensively in the topics involving electrolysis and electrochemical cells in the following year.

Regular Programme of Instruction

A chemistry scheme of work based on the syllabus requirements was developed for the year in collaboration with all teachers who would be teaching the subject. The content to be covered in each of the topics was detailed on a weekly basis. Each of the topics had to be covered within a stipulated time frame followed by a common topic test that was to be administered on a particular week. In general, students were only required to learn and remember the chemical equations as well as the ionic equations, where relevant, with no specific emphasis on understanding the triplet relationship.

Chemical equations as symbolic representations were first introduced in Grade 9 when students were required to construct and interpret chemical and ionic equations with state symbols to enable them to perform stoichiometry computations involving masses, moles and volumes of solids, aqueous solutions and gases. A subsequent topic required students to be able to describe the characteristic properties of acids in reactions with metals, bases and carbonates, and to describe the characteristic properties of bases in reactions with acids. The only direct reference to submicroscopic representations involved describing the meanings of acids and alkalis in terms of the ions that these substances contain or produce in aqueous solution, and describing neutralisation as a reaction between H^+ ions and OH^- ions to produce water. Students were also required to know the chemical reactions for preparing soluble salts from acids and bases, and for preparing insoluble salts using ionic precipitation reactions. In the final topic in Grade 9 students were introduced to the metal reactivity series when they revisited the reactions of metals with dilute acids. In addition, students were required to describe the reactivity series as relating to the tendency of a metal to form its positive ion illustrated by the reactions of the metal with aqueous solutions of ions of other metals.

Students had the opportunity to carry out most of the chemical reactions referred to above in preparation for the qualitative analysis component of the practical examination that involved the identification of several ions and gases. The only other practical experience involving chemical reactions that students would have encountered was when they prepared samples of soluble and insoluble salts in the laboratory using one or more methods previously discussed in class.

Alternative Programme of Instruction

An alternative programme of instruction aimed at reinforcing the use of the triplet relationship when describing and explaining the seven types of chemical reactions was developed by the second author and incorporated into the prescribed scheme of work. In order to delineate the content of the alternative instructional programme, the concept map in Fig. 7.1 (Chandrasegaran, 2004) was developed. The concept map encapsulates the characteristics of the seven chemical reactions and indicates

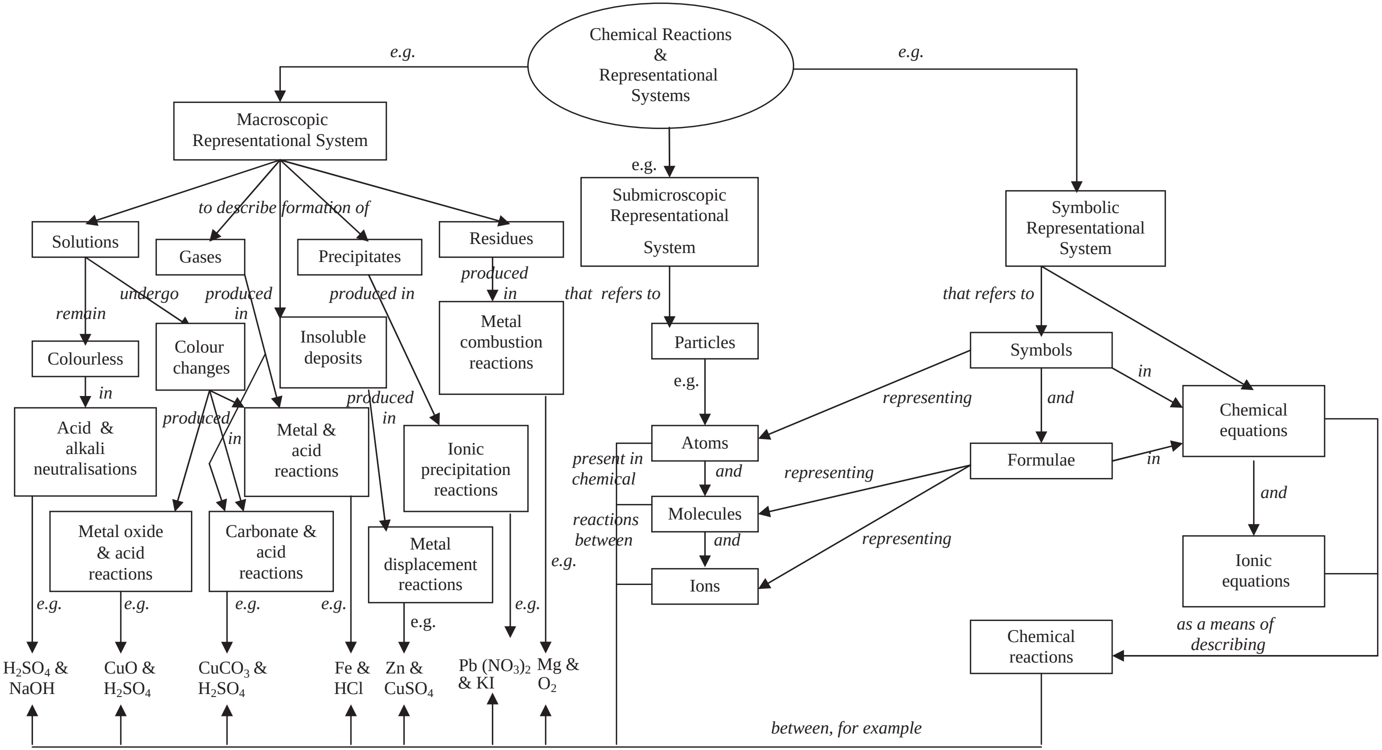


Fig. 7.1 Concept map for describing chemical reactions using multiple levels of representation

the multiple levels of representation involved. Seven separate concept maps were further developed one for each of the chemical reactions. An example of the concept map for the chemical reaction between dilute acids and reactive metals is found in Fig. 7.2 (Chandrasegaran, 2004).

Besides the prescribed scheme of work that was described earlier, emphasis was placed specifically on the relevance of the three representations during instruction. The additional features of the alternative instructional programme are summarised in Fig. 7.3. Laboratory lessons as well as classroom demonstrations were planned and implemented for each of the chemical reactions included in this study taking these features into account. Notes to illustrate the development of the lesson involving the chemical reaction between zinc powder and aqueous copper(II) sulphate are provided in Fig. 7.4.

At the end of the nine months of instruction the 15-item RSCRDI was administered to the 65 students in the two classes (as well as to 76 students in two other

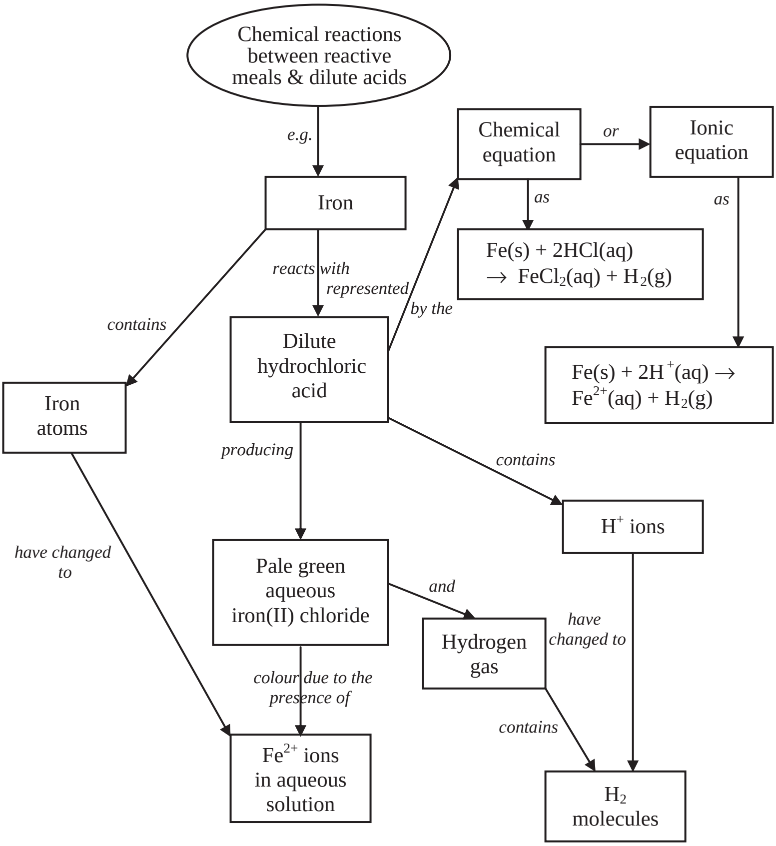
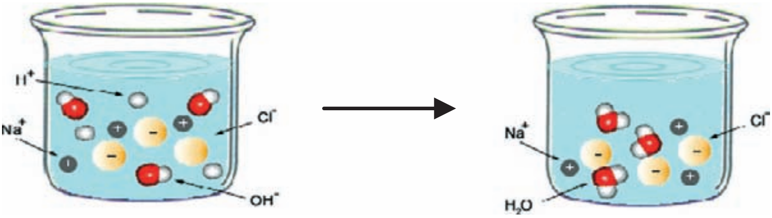


Fig. 7.2 Concept map for describing the chemical reaction between iron powder and dilute hydrochloric acid

- *Additional laboratory activities* to familiarise students with chemical reactions.
- *Explanation* of the observed chemical changes at the *particulate and symbolic levels*. (An example is illustrated below for a strong acid–strong alkali neutralisation reaction).



Particles before and after a strong acid–strong alkali neutralisation reaction

(Adapted from British Columbia Institute of Technology website: http://www.bcit.ca)

- *Emphasising* the significance of *coefficients and subscripts* in chemical and ionic equations.
- *Deducing ionic equations* from observed chemical changes, not by mechanically 'cancelling out' 'spectator ions' in chemical equations.

Fig. 7.3 The main features of the alternative instructional programme

classes that followed the regular programme of instruction). The RSCRDI was developed using the procedure proposed by Treagust (1995), and involved identifying student conceptions about the triplet relationship in chemical reactions that were displayed in students' written explanations, from findings reported in the research literature as well as from the authors' previous teaching experience. The first tier of each item required students to make a content choice related to the question. The second tier involved selecting a justification for the response that was chosen in the first tier. The 15 items were content validated by two science education professors and a teaching colleague of the second author. The instrument had an acceptable Cronbach alpha reliability coefficient of 0.65 as it is greater than the threshold value of 0.5 for multiple choice items quoted by Nunally & Bernstein (1994). Two items from the instrument relating to the chemical reactions of aqueous solutions of lead(II) nitrate with aqueous potassium iodide and with aqueous sodium iodide are illustrated in Fig. 7.5. A complete version of the diagnostic instrument may be obtained from the first author.

An Evaluation of the Efficacy of the Programme

An examination of the percentage distribution of the scores on the RSCRDI showed a trend towards higher scores for the students who were involved in the alternative instructional programme compared to students in the regular programme of instruction. Scores in the range from 10 to 15 marks were obtained by 71% of students involved in the alternative instructional programme but by only 47% of students who were involved in the regular programme (Fig. 7.6).

1 Aims of the lesson

- Identify students' prior knowledge about the metal activity series.
- Develop students' understanding of the triplet relationship when describing and explaining the displacement reaction between zinc and aqueous copper(II) sulphate.
- Deduce the ionic equation for the chemical reaction.
- Apply understanding of the triplet relationship to new and unfamiliar displacement reactions.

2 Lesson Outline

- Recall features of the metal activity series.
- Introduce concept of displacement reaction illustrating with the full balanced chemical equation for the reaction between zinc and aqueous copper(II) sulphate.
- Students, working in pairs, add zinc powder to some aqueous copper(II) sulphate in a test-tube, shake the mixture and allow to stand.
- Students discuss changes in pairs and record the changes.
- Elicit students' responses for the changes observed.
- Whole class discussion guided by pre-prepared set of questions as a guide. (Expected responses for several questions are provided in parentheses).
  - What was the blue colour of aqueous copper(II) sulphate due to?
    (*The presence of Cu*$^{2+}$ *ions.)*
  - How do you explain the formation of a colourless solution?
    (*Cu*$^{2+}$ *ions are no longer present in solution. / Presence of Zn*$^{2+}$ *ions in solution*.)
  - What is the brown deposit most likely to be?
    (*Metallic copper*.)
  - How was the metallic copper produced?
    (*Cu*$^{2+}$ *ions gained two electrons each*.)
  - What has happened to the zinc powder?
    (*Zinc atoms have lost two electrons each to produce Zn*$^{2+}$ *ions in aqueous solution*.)
  - How could we represent these changes using an equation?
    $[Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu.]$
  - What does this ionic equation tell us about the changes at the macroscopic level?
  - What does this ionic equation tell us about the changes at the particulate level?
- Using the metal reactivity series, students are to predict if a chemical reaction would occur when a coil of copper wire is placed in some aqueous silver nitrate in a test-tube.
- Students are to predict the macroscopic changes that they would expect, given the balanced chemical equation for the above reaction.
- Demonstrate the chemical reaction between copper and aqueous silver nitrate.
- Discuss the observed changes using submicroscopic and symbolic representations.
- Students deduce the ionic equation for the chemical reaction.
- Summarise explanation of chemical changes in the two displacement reactions using the triplet relationship.

Fig. 7.4 Summary of lesson to introduce multiple levels of representation

Item 12

Colourless aqueous solutions of lead(II) nitrate and potassium iodide, KI, are mixed together. A yellow powdery precipitate of lead(II) iodide, PbI_2, is immediately produced.
The chemical equation for the reaction is

$$Pb(NO_3)_2(aq) + 2KI(aq) \rightarrow PbI_2(s) + 2KNO_3(aq).$$

Which of the following is the ***ionic equation*** for the reaction that has occurred?

A $Pb^{2+}(aq) + 2I^{-}(aq) \rightarrow PbI_2(s)$
B $K^{+}(aq) + NO_3{}^{-}(aq) \rightarrow KNO_3(aq)$
C $Pb^{2+}(NO_3{}^{-})_2(aq) + 2K^{+}I^{-}(aq) \rightarrow Pb^{2+}(I^{-})_2(s) + 2K^{+}NO_3{}^{-}(aq).$

The ***reason*** *for my answer is*:

1 Potassium nitrate is produced in the chemical reaction.
2 The K^+ and $NO_3{}^-$ ions remain unchanged in aqueous solution as 'spectator ions'.
3 All ions involved in the reaction must be represented in the ionic equation.

Item 13

The salt solution, sodium iodide, NaI, was used in place of aqueous potassium iodide, KI, in Item 12. A yellow powdery precipitate was again produced.
The chemical equation for the reaction is

$$Pb(NO_3)_2(aq) + 2NaI(aq) \rightarrow PbI_2(s) + 2NaNO_3(aq).$$

The ***ionic equations*** for both the reactions involving aqueous lead(II) nitrate are
A similar. B different.
The ***reason*** *for my answer is*:

1 The 'spectator ions' are different in both the chemical reactions.
2 Both reactions result in the formation of insoluble lead(II) iodide, PbI_2.
3 Potassium iodide and sodium iodide both produce the same number of ions in aqueous solution.
4 Two moles each of potassium iodide and sodium iodide are required for reacting with one mole of lead(II) nitrate.

Fig. 7.5 Items from the RSCRDI involving the chemical reactions between aqueous solutions of lead(II) nitrate with potassium iodide and with sodium iodide

An ANOVA analysis was performed on the RSCRDI scores of the two groups of students in order to evaluate the efficacy of the alternative programme to facilitate understanding of the triplet relationship. A strong significant difference in the score means was indicated by the relatively high F value [$F(1, 141) = 14.8$, $p < .001$]. Also, there was a moderate to large actual difference in the mean scores of the two groups, indicated by an effect size, eta^2 of 0.10. A value of 0.14 and above indicates a large difference in the effects of the two modes of instruction (Pallant, 2005), suggesting that the alternative programme was more effective in facilitating understanding of the triplet relationship.

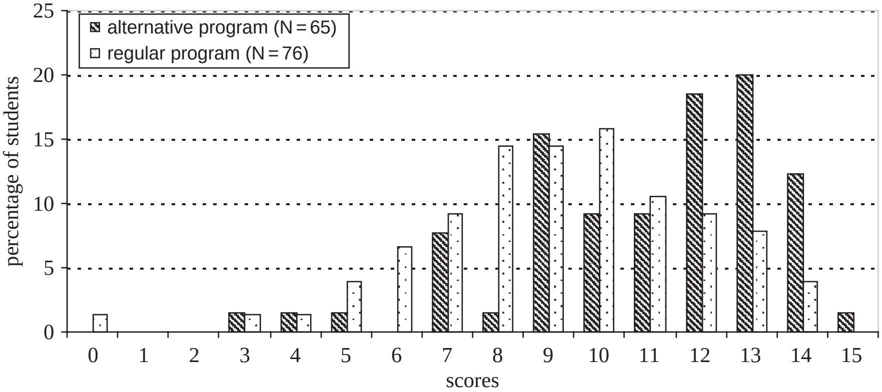


Fig. 7.6 Percentage distribution of RSCRDI scores for Grade 9 students who participated in the alternative programme and the regular programme

Existing Student Conceptions After the Programme

Students' responses to the 15 items were analysed to identify any patterns of conceptions that could emerge in their use of the triplet relationship. In general, students in the alternative instructional programme displayed a high level of proficiency in the use of the triplet relationship though several student conceptions were evident despite the emphasis that was placed to facilitate their understanding of the triplet relationship. This outcome was not unexpected as student conceptions, by nature, are often resistant to instruction (Bodner, 1986).

The student conceptions that were displayed could be categorised into three main types, namely: (1) confusion between macroscopic and submicroscopic representations, (2) extrapolation of bulk macroscopic properties of matter to the submicroscopic level and (3) confusion over the multi-faceted significance of chemical symbols, chemical formulas as well as chemical and ionic equations. Student conceptions held by at least 10% of the students who were involved in the alternative instructional programme were identified. Several examples of student conceptions involving the use of the triplet relationship are discussed in the next section.

Confusion Between Macroscopic and Submicroscopic Representations

When iron powder reacts with dilute hydrochloric acid, a green solution of aqueous iron(II) chloride is produced (explanation at the macroscopic level). The colour change of the solution from colourless to green may be attributed to the presence of Fe^{2+} ions in solution (explanation at the submicroscopic level). Several students (15%), however, suggested that atoms of iron and chlorine had turned green as a result of the chemical reaction. In this instance, students indicated the mistaken belief that the green solution of aqueous iron(II) chloride (macroscopic level of representation) was produced from atoms of iron and chlorine (submicroscopic level of representation). In another instance involving the burning of magnesium ribbon in air, 14% of students suggested that the metal magnesium (instead of the particles in the metal) has a charge of +2. This suggestion may have been associated with the model that is used in the syllabus for the explanation of metallic bonding that is regarded as resulting from the electrostatic attractions between positive nuclei of metal atoms and the 'sea' of mobile valence electrons.

Extrapolation of Macroscopic Properties of Matter to the Submicroscopic Level

The extrapolation of physical attributes of substances to the submicroscopic level of representation was evident when students explained the changes in the displacement reaction between zinc powder and aqueous copper(II) sulphate. The decrease in intensity of the blue colour of the solution was attributed by 31% of students to the removal of *blue individual* Cu^{2+} *ions* from aqueous solution. The suggestion that *individual* Cu^{2+} ions (the submicroscopic level) are blue may be indicative of the extrapolation of the blue colour of the aqueous copper(II) sulphate (the macroscopic level) to the colour of individual Cu^{2+} ions (the submicroscopic level). Thirty-one percent of students also suggested that *reddish-brown, insoluble individual atoms of copper* were produced in this chemical reaction, again suggesting extrapolation of the bulk properties of copper, i.e., being reddish-brown and insoluble in water (the macroscopic level), to individual copper atoms having these properties (the submicroscopic level).

In the chemical reaction between iron(II) oxide powder and dilute hydrochloric acid, the solution changed from colourless to light green. The suggestion by 15% of students that *green individual* Fe^{2+} *ions* were present in aqueous iron(II) chloride again indicated possible extrapolation of the bulk colour of the pale green aqueous iron(II) chloride (the macroscopic level) to the colour of individual Fe^{2+} ions (the submicroscopic and symbolic levels) in solution.

Confusion over the Symbolic Representational System

Students' difficulty with deriving ionic equations was very apparent in several instances. For example, 11% of students (albeit relatively low) were unable to deduce, using submicroscopic and symbolic representations, that when any strong acid reacted with any strong alkali the changes would be similar because the chemical reaction in each case was essentially one between H^+ ions from the dilute acid and OH^- ions from the alkali (using submicroscopic and symbolic representations). The ionic equation (symbolic representation) would, therefore, be the same for all chemical reactions irrespective of which strong acid and strong alkali were used.

The confusion was probably caused by the different stoichiometries of the balanced chemical equations, with one mole of sodium hydroxide reacting with one mole of dilute hydrochloric acid but two moles of the alkali reacting with one mole of dilute sulphuric acid.

A similar observation was made in the ionic precipitation of lead(II) iodide. When aqueous solutions of potassium iodide and sodium iodide were separately added to aqueous lead(II) nitrate, 12% of students believed that the ionic equation for the precipitation reactions was different in the two instances even though the stoichiometry of the two chemical reactions had no influence on the ionic equation.

When interpreting the chemical equation for the reaction between aqueous sodium hydroxide and dilute nitric acid, 20% of students appeared to hold the view that Na^+ and NO_3^- ions (submicroscopic and symbolic representations) had reacted in aqueous solution to produce aqueous sodium nitrate. It was not apparent to these students that the net chemical reaction had only involved removal of H^+ and OH^- in aqueous solution to produce molecules of H_2O.

Other Inappropriate Conceptions

Apart from the three broad categories of student conceptions discussed above, students displayed several inappropriate conceptions relating to the structural properties of substances. For example, 14% of students suggested that Mg^{2+} ions were present in magnesium ribbon. A second example involved the chemical reaction between copper(II) oxide powder and dilute sulphuric acid. In this instance, 25% of students suggested that Cu^{2+} ions were present only in aqueous solution but not in the solid and liquid states. This view was rather unexpected because students had earlier been introduced to ionic and covalent compounds. It is likely that students had merely rote-learned the general rule without sufficient understanding that ionic solids are formed between metallic and non-metallic elements.

Conclusions for Teaching and Research

Despite the limitations of this study that involved students from a single school, the findings about the efficacy of the alternative instructional programme and the use of the diagnostic instrument make a significant, albeit limited, contribution to our knowledge about evaluating secondary school students' proficiency with regard to the triplet relationship between macroscopic, submicroscopic and symbolic representations when describing and explaining chemical reactions.

Analysis of students' responses on the diagnostic test indicated, in several instances, their understanding of the triplet relationship when describing and explaining the chemical reactions. For example, in the chemical reaction between a strong acid and strong alkali, most students were able to relate the changes at the macroscopic level (production of a solution neutral to litmus indicator) to the changes at the submicroscopic and symbolic levels of representation (removal of equal numbers of H^+ ions and OH^- ions from aqueous solution). In another example involving the chemical reactions of aqueous lead(II) nitrate with aqueous solutions of potassium iodide and sodium iodide, respectively, students were generally able to associate the same observed change at the macroscopic level (the production of a yellow precipitate of lead(II) iodide) in both reactions to the same change at the submicroscopic level using symbolic representations (removal of Pb^{2+} and I^{-} ions represented by the same ionic equation).

However, analysis of students' responses to the items in the RSCRDI has shown that despite efforts during instruction to facilitate students' use of multiple levels of representation, several student conceptions still persisted among the students who were involved in this study. Administration of the RSCRDI to evaluate students' understandings about the use of multiple levels of representation will provide useful information to teachers in the planning of classroom instruction by incorporating strategies that challenge students' conceptions in order to facilitate more meaningful understandings.

The resistance to change of students' conceptions is not unexpected as these conceptions are deep-rooted and often 'difficult to shift, and can offer a serious barrier to effective teaching' (Tytler, 2002, p. 15). For example, students in this study demonstrated confusion between macroscopic and submicroscopic representations when they suggested that magnesium (instead of the particles in magnesium) has a charge of $+2$, and that iron and chlorine atoms turned green when iron powder reacted with dilute hydrochloric acid. In other instances students displayed a tendency to extrapolate the bulk macroscopic properties of matter to the submicroscopic level by suggesting for example that insoluble, reddish-brown copper atoms were produced in the displacement reaction between zinc powder and aqueous copper(II) sulphate. They also attributed the fading of the blue colour of the solution to the removal of individual *blue* Cu^{2+} *ions*, as a result of extrapolating the blue colour of the bulk solution to the submicroscopic level of representation. Students were also relatively uncertain about the significance of symbolic representations, especially with regard to ionic equations. This weakness was evident in their understanding of the chemical reactions between different pairs of strong acids and strong alkalis, different metal oxides and different dilute acids and ionic precipitation of lead (II) iodide on adding aqueous lead(II) nitrate to different aqueous solutions of iodides. Despite efforts in the alternative instructional programme to address these issues, it was not evident to several students that the changes at the submicroscopic level were essentially the same for each pair of reactants, and that as a result the ionic equation was identical in each case.

Implications for Teaching and Learning

Several implications for classroom practice are evident from the results of this study.

The efficacy of the alternative instructional programme in facilitating students' understanding of the triplet relationship lends support to the instructional strategies that were implemented in the programme. Also, the RSCRDI has been successfully utilised as a convenient diagnostic tool for assessing students' proficiency in the use of the triplet relationship. Introduction of the alternative instructional programme and the diagnostic instrument in workshops for teachers could contribute in several ways to their professional development.

First, teachers need to be made aware of the need to place greater emphasis on the purposeful use of multiple levels of representation when describing and explaining chemical phenomena during classroom instruction. All too often teachers take for granted that students are able to switch back and forth with ease between different levels of representation. The findings of this study have shown that students' competence in the use of the triplet relationship to describe and explain chemical reactions was enhanced as a result of the instruction.

Second, students should be provided with opportunities to perform the chemical reactions themselves and discuss with their peers the observed changes in terms of the particles and chemical and ionic equations involved. When faced with time constraints, teachers could demonstrate some of the reactions and then provide opportunities for small group discussions.

Third, students' understanding of the triplet relationship for a particular type of reaction may be further consolidated by carrying out additional similar reactions using different reactants (e.g., using several metal oxides to react with different dilute acids will help illustrate the similarities in the chemical reactions although different salts are produced). Once students become aware of the similarities in the chemical reactions, they would be more likely to meaningfully deduce the ionic equations for the chemical reactions instead of the common practice of 'cancelling out' the 'spectator ions' from the overall balanced chemical equation.

Fourth, classroom instruction may be organised in a manner that takes into account students' conceptions similar to the ones that have been identified in this study in order to improve students' facility in understanding the triplet relationship relating to chemical reactions. By making students aware of conceptions that are not scientifically acceptable and by promoting discussions with the teacher and with peers in small groups, students may be led to arrive at more fruitful understandings of the changes that occur in chemical reactions making use of the triplet relationship.

Finally, the diagnostic instrument may be administered before commencing a particular topic in order to gauge students' prior understanding of the associated concepts. At the same time, the use of the instrument as a formative assessment tool will enable the teacher to take appropriate measures to challenge any students' conceptions that may become evident during the lesson or plan for remediation with small groups of students that experience difficulties.

References

Anderson, G. (2004). *Fundamentals of educational research* (2nd ed.). London, England: Routledge Falmer.

Andersson, B. (1986). Pupils' explanations of some aspects of chemical reactions. *Science Education, 70*, 549–563.

Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. London: Holt, Rinehart & Winston.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*(1), 64–66.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1987). Students' visualization of a chemical reaction. *Education in Chemistry, 24*, 117–120.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1988). Theories, principles and laws. *Education in Chemistry, 25*, 89–92.

Bodner, G. M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education, 63*, 873–878.

Bodner, G. M. (1991). I have found you an argument: The conceptual knowledge of beginning chemistry graduate students. *Journal of Chemical Education, 68*(5), 385–388.

Boo, H. K. (1998). Students' understanding of chemical bonds and the energetics of chemical reactions. *Journal of Research in Science Teaching, 35*(5), 569–581.

Chandrasegaran, A. L. (2004). *Diagnostic assessment of secondary students' use of three levels of representation to explain simple chemical reactions*. Unpublished doctoral dissertation, Curtin University of Technology, Perth, Australia.

Chandrasegaran, A. L., Treagust, D. F., & Mocerino, M. (2007). The development of a two-tier multiple-choice diagnostic instrument for evaluating secondary school students' ability to describe and explain chemical reactions using multiple levels of representation. *Chemistry Education Research and Practice, 8*(3), 293–307.

Duit, R., & Treagust, D. F. (1995). Students' conceptions and constructivist teaching approaches. In B. J. Fraser & H. J. Walberg (Eds.), *Improving Science Education* (pp. 46–49). Chicago, IL: The National Society for the Study of Education.

Duit, R., & Treagust, D. F. (1998). Learning in science – from behaviourism towards social constructivism and beyond. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (Vol. 1, pp. 3–25). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Gabel, D. (1998). The complexity of chemistry and implications for teaching. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (Vol. 1, pp. 233–248). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look at the future. *Journal of Chemical Education, 76*(4), 548–554.

Gabel, D., Samuel, K. V., & Hunn, D. (1987). Understanding the particle nature of matter. *Journal of Chemical Education, 64*(8), 695–697.

Garnett, P. J., Garnett, P. J., & Hackling, M. W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education, 25*, 69–95.

Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*, 611–628.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning, 1*, 75–83.

Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemical Education, 70*(9), 701–705.

Keig, P. F., & Rubba, P. A. (1993). Translations of the representations of the structure of matter and its relationship to reasoning, gender, spatial reasoning, and specific prior knowledge. *Journal of Research in Science Teaching, 30*(8), 883–903.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*(9), 949–968.

Merriam, S. B. (1998). *Qualitative research and case study applications in education* (2nd ed.). San Francisco, CA: Jossey-Bass.

Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education, 69*, 191–196.

Nakhleh, M. B., & Krajcik, J. S. (1994). Influence of levels of information as presented by different technologies on students' understanding of acid, base, and pH concepts. *Journal of Research in Science Teaching, 31*(10), 1077–1096.

Nunally, J. C., & Bernstein, I. H. (1994). *Psychometric theory* (3rd ed.). New York: McGraw-Hill.

Nurrenbern, S. C., & Pickering, M. (1987). Concept learning versus problem solving: Is there a difference? *Journal of Chemical Education, 64*, 508–510.

Pallant, J. (2005). *SPSS survival manual* (2nd ed.). Crows Nest, Australia: Allen & Unwin.

Seddon, G. M., & Eniaiyeju, P. A. (1986). The understanding of pictorial depth cues, and the ability to visualise the rotation of three-dimensional structures in diagrams. *Research in Science and Technological Education, 4*(1), 29–37.

Tan, K. C. D., Goh, N. K., Chia, L. S., & Treagust, D. F. (2002). Thinking and understanding in qualitative analysis practical work. *Teaching and Learning, 23*(1), 69–75.

Treagust, D. F. (1995). Diagnostic assessment of students' science knowledge. In S. M. Glynn & R. Duit (Eds.), *Learning science in the schools: Research reforming practice* (Vol. 1, pp. 327–436). Mahwah, NJ: Lawrence Erlbaum.

Treagust, D. F., & Chittleborough, G. (2001). Chemistry: A matter of understanding representations. In J. Brophy (Ed.), *Subject-specific instructional methods and activities* (Vol. 8, pp. 239–267). Oxford, UK: Elsevier Science Ltd.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education, 25*(11), 1353–1368.

Tytler, R. (2002). Teaching for understanding in science: Student conceptions research, and changing views of learning. *Australian Science Teachers Journal, 48*(3), 30–35.

Chapter 8
Linking the Macroscopic and Sub-microscopic Levels: Diagrams

Bette Davidowitz and Gail Chittleborough

> *Pictures seldom can capture all the subtle nuances of a model, but good pictures and movie clips are not only what are best remembered, they also often enable us to take the next steps in both teaching and research. (Zare, 2002)*

Abstract Explanations of chemical phenomena are nearly always focused at the sub-micro level, a level that cannot be observed, yet are normally provided with diagrams at the symbolic level. These diagrams represent the macro and sub-micro levels of matter. The connections between the macro level and the diagrams of the sub-micro level are not always apparent to students, indicating a need for chemical diagrams to be used carefully and explicitly. Having students draw and annotate chemical diagrams representing chemical phenomena at the sub-micro level can provide some insight into their understanding of chemistry at the macro level. Misinterpretation of diagrams can occur when the representations are not understood, when links are not made between the macro and sub-micro levels, or when the diagram is unfamiliar. Responding to these difficulties, strategies based on research and our experiences of teaching with diagrams are suggested for the choice and use of chemical diagrams depicting the sub-micro level in the teaching and learning of chemistry. These strategies provide opportunities for learners to construct acceptable personal mental models of the sub-micro level.

Introduction

Chemical diagrams are one of the most commonly used forms of representation in teaching chemistry. They are symbolic representations that present images and information of the sub-micro or molecular level. Since the sub-micro level cannot be observed directly, chemical diagrams of this level are used in textbooks, on posters, in videos, in software programmes, etc. by teachers to describe the sub-micro level and explain chemical phenomena. They play an important role in helping students

---

B. Davidowitz (✉)
University of Cape Town, Rondebosch 7701, South Africa
e-mail: Bette.Davidowitz@uct.ac.za

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_9,

develop a mental image of the sub-micro level which is vital because chemical explanations nearly always depend on the sub-micro level. Some students regard the sub-micro level as unreal, vague and amorphous – with the sub-micro level being the least well understood of the three levels (Chittleborough & Treagust, 2008; Nicoll, 2003). The connections between the sub-micro level and the diagrams of the sub-micro level are not always apparent to students (Kozma and Russell, 1997; Treagust, Chittleborough, & Mamiala, 2003), indicating a need for chemical diagrams to be used carefully and explicitly. This chapter has two sections; firstly a description of types of diagrams of the sub-micro level and why they are important in teaching and learning chemistry and secondly an examination of exemplary ways of using diagrams effectively in the chemistry classroom. The chapter concludes with some implications for teaching.

Chemical Diagrams and Their Importance in Teaching and Learning

Chemical diagrams are used to represent chemical information, to help describe an idea, provide an explanation, present a visual image, to make predictions, deductions, motivate and form hypotheses. They can be static or dynamic, two- or three-dimensional, or single-particle vs. multiple-particle. Chemical diagrams of the sub-micro level include representations of the molecular, atomic and sub-atomic particles which may be represented as a single atom, particle or an array of particles which may for example be presented as diagrammatic representations. There are many examples of diagrams depicting both the sub-micro and symbolic levels and in some cases a diagram may contain graphs, diagrams of the sub-micro level of the chemical phenomena, chemical equations as well as explanatory text as shown in Fig. 8.1.

While expert chemists are able to interpret these diagrams, they pose a significant intellectual challenge for the novice (Gabel, 1999; Johnstone, 1993; Treagust & Chittleborough, 2001). With new technologies the variety and accuracy of chemical diagrams available is increasing (Tasker & Dalton, 2006). The visual impact of diagrams can enhance the development of mental models and lead to more connectedness in learning (Chittleborough & Treagust, 2008; Fiorea, Cuevasa, & Oser, 2003). As the chemical diagrams more closely represent the sub-micro level their explanatory potential has improved. An explanatory tool such as a diagram or an image can provide the learner with a way of visualising the concept and hence developing a mental model for the concept (Gabel, 1998). The value of a diagram in making the link with an abstract concept depends on it being consistent with the learners' needs and being pitched at the learners' level of understanding (Giordan, 1991).

Diagrams as Learning Tools

Diagrams are essential learning tools. Gobert and Clement (1999) suggest that diagrams can have more than illustrative purposes, expanding the purpose of diagrams to model construction and reasoning. In this way, chemical diagrams serve

Figure 8.1
The extent of dissociation for strong and weak acids.

The bar graphs show the relative numbers of moles and species before (left) and after (right) acid dissociation occurs.

A. When a strong acid dissolves in water, it dissociates completely, yielding H_3O^+ (aq) and A^- (aq) ions; virtually no HA molecules are present.

B. In contrast, when a weak acid dissolves in water, it remains mostly undissociated, yielding relatively few H_3O^+ (aq) and A^- (aq) ions.

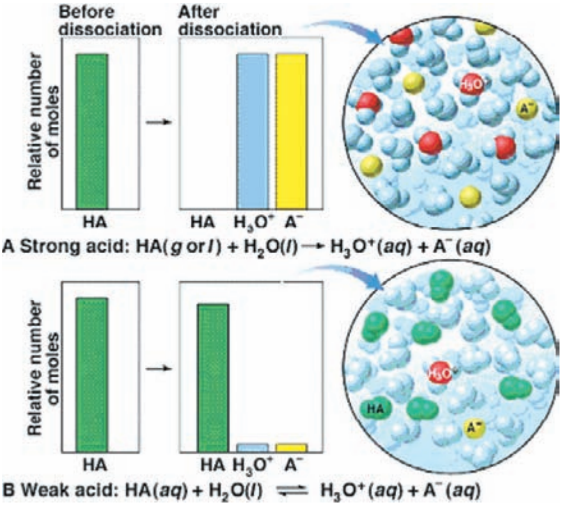


Fig. 8.1 Dissociation of strong and weak acids (from M. S. Silberberg, Chemistry: The molecular nature of matter and change, 3rd ed., McGraw Hill, 2003, p. 760, reproduced with permission of The McGraw-Hill Companies)

as significant teaching tools; however, the value depends on the students' understanding of the diagram. According to Mayer (2002) students learn by active selection, organisation and integration of information from auditory and/or visual inputs. Mayer developed eight principles of multimedia learning based on cognitive theory and design principles, two of which are relevant to the topic of chemical diagrams. These are the:

- *Multimedia principle*: A combination of words and pictures is more effective in promoting deeper learning than the use of words alone.
- *Coherence principle*: Extraneous words, sound or pictures can distract the learner and should be excluded in order to facilitate deeper learning.

Presentation of material using both pictures and text enables students to learn difficult concepts and principles. They retain what they have learned longer and are better able to use the concepts to solve problems than if the information had been presented using text only (Mayer, 2003). Kozma and Russell (2005) argue from a perspective of situated cognition by noting that representations allow discussion of objects and processes which cannot be seen. These representations take many forms such as symbols or diagrams which chemists use to communicate since they allow visualisation and communication of experimental observations and chemical phenomena. According to the authors

> "...the meaning of a representation is not embedded in the representation itself but is assigned to the representation through its use in practice – in this case of chemistry". (p. 130)

Expert chemists constitute a community of practice which uses representations to make sense of the activities of the discipline. Thus the conventions used in interpreting these representations are essential to the functioning of this community.

As chemists become integrated into the community of practice they use the representation systems as tools to communicate understanding and construct new meanings. The role of the expert is to induct the novice i.e. the student into the accepted uses of these representations, since helping students to relate the three commonly accepted levels of matter has the potential to enhance conceptual understanding (Gabel, 1999). Experts need to be cognisant that understanding the behaviour of substances at the molecular (sub-micro) level is recorded in terms of a representational language or notation e.g. a chemical equation or a reaction mechanism. The induction of new members into the community of practicing chemists requires careful scaffolding to develop competence in using the various forms of representation. For example Gabel (1993) reported that the use of overhead transparencies together with worksheets designed to link the sub-micro and symbolic levels led to an overall improvement in both students' understanding of the particulate nature of matter as well as their achievement scores in chemistry. A study by Sanger (2000) showed that students using visual material which focussed on the characteristics of pure substances and mixtures at the sub-micro level were more likely to identify particulate diagrams of liquids, pure substances and mixtures than students who received more traditional instruction. These results suggest that the use of teaching materials which contained particulate drawings was effective in enabling students to think about the classification of matter at the molecular level.

Sub-micro, Symbolic and Macro Levels

The sub-micro level is real, but is not visible and so it can be difficult to comprehend. As Kozma and Russell (1997) point out, 'understanding chemistry relies on making sense of the invisible and the untouchable' (p. 949). Explaining chemical reactions demands that a mental picture is developed to represent the sub-micro particles in the substances being observed. Chemical diagrams are one form of representation that contributes to a mental model. It is not yet possible to see how the atoms interact, thus the chemist relies on the atomic theory of matter on which the sub-micro level is based. This is presented diagrammatically in Fig. 8.2. The links from the sub-micro level to the theory and representational level is shown with the dotted line.

The real and visible characteristics of the macro level and the real and invisible characteristics of the sub-micro level portray the same substance only on a different

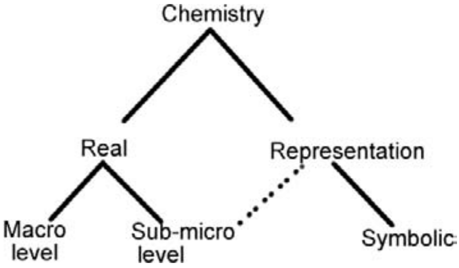


Fig. 8.2 The relationship between the three levels of chemical representations and real and represented chemical data

scale. Symbolic representations including chemical diagrams of the sub-micro level are critical in communicating these characteristics. The unique duality of chemical representations such as chemical diagrams, with links to both the macro and sub-micro levels simultaneously, highlights the complex nature of chemistry and the significant intellectual challenge facing any newcomer to the discipline who could be overwhelmed by the conceptual demands of shifting between the three domains of representations (de Jong and van Driel, 2004).

Visualisation

The sub-micro level cannot easily be seen directly, and while its principles and components are currently accepted as true and real, it depends on the atomic theory of matter. The scientific definition of a theory can be emphasised here with the picture of the atom constantly being revised. As Silberberg (2006) points out, scientists are ‘confident about the distribution of electrons but the interactions between protons and neutrons within the nucleus are still on the frontier of discovery’ (p. 54). This demonstrates the dynamic and exciting nature of chemistry. Appreciating this overview of how scientific ideas are developing may help students to expand their epistemology of science.

Johnstone (2000) emphasises the importance of beginning with the macro and symbolic levels (Fig. 8.3) because ‘both corners of the triangle are visualisable and can be made concrete with models’ (p. 12). The sub-micro level, by far the most difficult (Nelson, 2002), is described by the atomic theory of matter, in terms of particles such as electrons, atoms and molecules. It is commonly referred to as the molecular level. Johnstone (2000) describes this level simultaneously as the strength and weakness of the subject of chemistry: it provides strength through the intellectual basis for chemical explanations, but it also presents a weakness when novice students try to learn and understand it.

For many novice students the lack of a mental model appears to be a result of the sub-micro level being ignored or marginalised when compared to the macro and symbolic levels of representation (Wright, 2003). How the links between the three levels of representations can be made using the example of the rusting of iron is illustrated in Table 8.1. This contextual example intentionally presents the macro, sub-micro and symbolic levels simultaneously to help students link the various

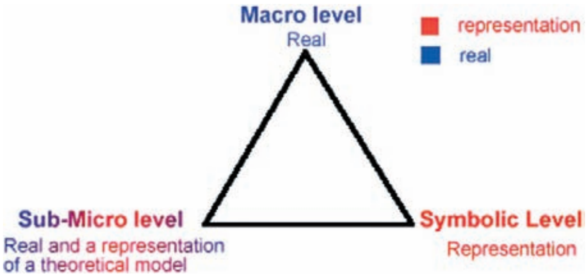


Fig. 8.3 The reality or representational status of the three levels of chemical representation of matter

Table 8.1 Description of the rusting of iron at each level of chemical representation of matter

	Level of Representation		
	Macro	Sub-micro	Symbolic
Real or Representation	Real	Real but too small to be seen with the naked eye.	Representation.
Description	Tangible; quantitative	The particulate or molecular level according to the atomic theory of matter.	A depiction which may or may not be accurate but helps to provide a mental image.
Perception	Visible	Cannot be seen with the naked eye, so mental image is based on descriptions, diagrams, explanations.	The model is a tool to help understand the real entity.

representations. Linking the sub-micro representations with other representations can be enhanced through the use of visualisation tools such as animations (Tasker & Dalton, 2006). For example Velázquez-Marcano, Williamson, Askenazi, Tasker, & Williamson (2004) report on the impact of using both video demonstrations and particulate animations in improving conceptual understanding, acknowledging that video alone was not as effective as when used in conjunction with animations. The recent sudden increase of images at the sub-micro level through advances in nanotechnology has the potential to provide the visualisation required to teach this level more effectively, even though the projections are still representations (Stevens, Owens, & Wuhrer, 2002).

How Does Metavisualisation Skill Relate to the Use of Chemical Diagrams?

The explosion in information computer technologies has meant that the quality, accuracy, detail and capabilities of visual representations is constantly improving to higher standards, along with lower costs and increased availability. Gilbert (2005) identifies that the 'significance of visualization in science education is being realised by a diverse group of specialists' (p. 23). The use of visual representations is commonplace and expected, especially among learners who have grown up in a visual-learning domain. Gilbert proposes that visualisation involves more than just forming a mental image but rather involves metacognition, requiring the learner to navigate through multiple images, make assessments and interpretations of images. This skill Gilbert (2005) refers to as *metavisualization* i.e. 'metacognition in respect of visualization' (p. 15). Because students' visualisation skills and their metavisual capacity impact on their learning both need to be considered in pedagogical approaches. The metavisual capabilities can be assessed in terms of the learners' 'spatial visualization' i.e. being able to mentally manipulate spatial forms, 'closure flexibility'– i.e. the speed of identifying visual patterns, 'spatial relations' and their metacognitive capabilities (Gilbert, 2005, p. 23).

Metavisualisation is particularly significant with respect to the sub-micro level which is abstract and difficult to represent accurately. Since single diagrams have limitations multiple diagrams are commonly used. The skill of interpreting and translating from one diagram to another embodies the notion of metavisualisation. Chemical diagrams have a significant role in representing the multiple representations that characterise the subject. The consistent and repeated use of the three levels of representation namely macro, sub-micro and symbolic occurs in many chemical explanations across all chemistry topics. This common approach presents a way of knowing about chemistry that should promote more meaningful understanding.

Limitations of Chemical Diagrams

Chemical diagrams of atoms and molecules are usually a snapshot of an instant in time depicting a single successful reaction. By focusing only on the successful reaction, the unsuccessful reactions are forgotten and the probability of success is not represented. For example, there is a risk that the kinetic molecular theory relating to the motion of the sub-atomic particles such as the magnitude of the number of chemical species in the vessel and the constant movement and the many unsuccessful collisions is not appreciated (Krajcik, 1991). This omission in understanding the events of the kinetic molecular theory highlights the risk that a representation can be taken out of context and the meaning jeopardised. Bucat (2004) highlights the importance of recognising the appropriate 'level' – whether it is focussing on individual particles or considering observable properties or somewhere in-between. The common practice of focusing on individual particles may perpetuate misconceptions (Ben-Zvi, Eylon, & Silberstein, 1987). Explanations of chemical phenomena usually rely on the behaviour of the sub-micro particles that are represented symbolically. Consequently, the students' understanding of all three levels is central to the success of any explanation.

The use of static diagrams to depict dynamic processes was investigated by Sanger and Phelps (2007) who used the particulate question developed by Nurrenbern and Pickering (1987) to probe students' conceptual understanding of kinetic molecular theory and the behaviour of ideal gas particles. Besides choosing the correct sub-micro representation depicting the container after cooling of the gas sample, students were asked to provide an explanation of the behaviour of gas particles at the molecular level. The authors raised concerns related to the validity of the question and its ability to measure conceptual understanding of the behaviour of gas particles namely that particle motion cannot be shown using a static sub-micro representation as depicted in the choice of answers provided. Some of the students in the study were reluctant to choose the correct answer since the diagram provided did not appear to be different from the starting picture despite the fact that they realised that decreasing the temperature would affect the gas particles. Sanger and Phelps suggest that this question could be improved by using animation to show the critical attribute of particle motion. In a follow-up study, Sanger, Campbell, Felker, and Spencer (2007) used an animated version of the question and found that it did assist more students to choose the correct answer than using the static drawing alone.

Chemical diagrams can perpetuate misinformation. Unfortunately, students often transfer the macro properties of a substance to its sub-micro particles, observing for example that sulphur is yellow, so believing that the atoms of sulphur are yellow also. Indeed, this is not surprising considering the graphical representation of yellow circles in textbooks to represent the atoms (Andersson, 1990; Garnett, Garnett, & Hackling, 1995; Krnel, Watson, & Glazar, 1998). To overcome this problem, Gabel, Briner, and Haines (1992) recommend that teachers provide physical examples or at least descriptions of the chemicals in the problems, besides representations, so that students can establish their own links between the three major levels for portraying the chemical phenomena.

In a study of the Vischem project which developed animated diagrams at the sub-micro level, Tasker & Dalton (2006) show how diagrams and animations can be used to help address common misconceptions. For example, students observe an animation of an ionic solution addressing the common misconception ‘that the ions do not interact with the solvent and, more seriously, are clustered together in their ionic formula units’ (p. 152). The students then construct their own representations, drawing on their experiences with animations, equations and observations etc. Providing the opportunity for students to receive feedback on their own understanding helps them to identify and reconcile misconceptions. Tasker and Dalton have identified the pedagogical significance of students drawing their own representations:

> “Student drawings and descriptions of their conceptions of structures and processes at the molecular level often reveal misconceptions not detectable in conventional equation-writing questions” (p. 155).

The pedagogical power of this approach is in the students’ construction and reconciliation of their own representations that portray their understanding.

While sub-micro diagrams in text books are almost invariably depicted in colour, for example Fig. 8.1, this would be a limitation to using sub-micro diagrams in teaching and learning in some classrooms where teachers would not be able to justify the expense of printing materials in colour. Diagrams drawn in black and white would have to be provided with a key to assist learners to interpret them; this key may add an extra level of complexity to their use and teachers would do well to provide adequate scaffolding when designing their own worksheets.

What Does Research Indicate that Students Understand from Chemical Diagrams?

The students’ understanding of the three levels of chemical representation of matter forms the foundation of their conceptual understanding of chemistry. Kozma and Russell (1997) identified significant differences in the representational competence of experts and novices, suggesting that the development of skills in identifying and transforming representations is advantageous to learning chemistry. Students may not know the names that have been assigned to the levels but have demonstrated an ability to transfer from one to another, making analogical relations (Collins & Gentner, 1987; Gabel, 1998).

According to Hinton and Nakhleh (1999), macro, sub-micro and symbolic representations are each appropriate tools to illustrate various aspects of chemical reactions. Figure 8.4 shows a typical text book diagram using the various types of representations for a simple chemical reaction.

This diagram may appear trivial to the expert chemist but for a novice it contains much information about the chemical reaction at both the sub-micro and symbolic levels presented in multiple representational formats. Unless teachers are explicit in their use of these representations it is unrealistic to assume that students would develop the same ability to choose an appropriate representation for a given process. It is possible that students can use and understand the representations without being able to see how they are related. Several authors (Hinton and Nakhleh, 1999; Kozma and Russell, 1997; Nurrenbern and Pickering, 1987) suggest that students are made aware of all three levels of representations and given opportunities to use them in solving problems.

The schematic representation of chemical reactions is a powerful tool to probe the understanding of processes most commonly presented at the symbolic level only. About 20 years ago, Nurrenbern and Pickering (1987) used diagrams depicting the sub-micro level of chemistry and showed that while students could solve mathematical chemistry problems, they had difficulties in answering conceptual problems covering the same topics. This was especially the case for problems involving the particulate nature of matter. Several authors have investigated the use of sub-micro representations in assessing students' understanding of chemical concepts.

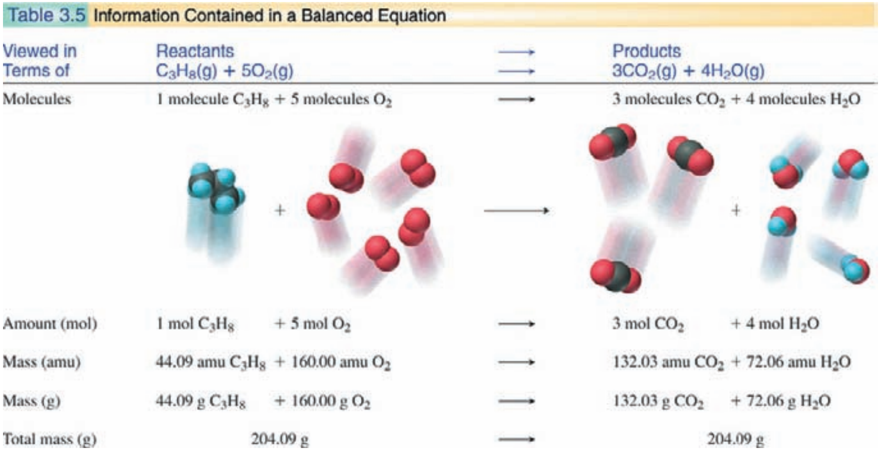


Table 3.5 Information Contained in a Balanced Equation

Viewed in Terms of	Reactants $C_3H_8(g) + 5O_2(g)$	→	Products $3CO_2(g) + 4H_2O(g)$
Molecules	1 molecule C_3H_8 + 5 molecules O_2	→	3 molecules CO_2 + 4 molecules H_2O
Amount (mol)	1 mol C_3H_8 + 5 mol O_2	→	3 mol CO_2 + 4 mol H_2O
Mass (amu)	44.09 amu C_3H_8 + 160.00 amu O_2	→	132.03 amu CO_2 + 72.06 amu H_2O
Mass (g)	44.09 g C_3H_8 + 160.00 g O_2	→	132.03 g CO_2 + 72.06 g H_2O
Total mass (g)	204.09 g	→	204.09 g

Fig. 8.4 Information contained in a balanced equation (from M. S. Silberberg, Chemistry: The molecular nature of matter and change, 4th ed., McGraw Hill, 2006, p. 106, reproduced with permission of The McGraw-Hill Companies)

For example, Chittleborough and Treagust (2008) found a great variation in students' ability to explain specific diagrams at either the macro or sub-micro level. Students' interpretation and understanding of chemical diagrams was dependent on each individual's understanding of the sub-micro level of matter.

Molecular visualisation of the sub-micro level is the key to developing mental models of the level. Multimedia technology is being used increasingly and provides an opportunity to present multiple levels simultaneously in various formats such as video, animations and simulations e.g. Molecular Workbench, SMV: Chem, Connected Chemistry and 4M:Chem. Ardac and Akaygun (2004) investigated the effectiveness of multimedia-based instruction on students' understanding of chemical reactions. They found that connecting a visual display of related representations of the three levels of a chemical change does not guarantee that students will relate these together in a consistent manner. Ardac and Akaygun suggest that students should receive specific instruction to 'highlight the correspondence between the related representations' (p. 332). Onwu & Randall (2006) investigated students' understanding of the link between the sub-micro and macro levels and found that students had difficulties in imagining the macroscopic events in terms of the particulate model as represented by the sub-micro representations. They caution against a too hasty approach in teaching the basic concepts of particulate matter which ideally need time to develop.

While Kozma and Russell (2005) recommend the use of visualisation resources, the value of the various formats for various topics is debatable. Kozma and Russell confirm 'we are not able to say, given the state of the research, for which topics or students it is best to use animations versus still pictures or models' (p. 330). Ardac and Akaygun (2005) on the other hand favour the use of dynamic visuals (preferably on an individual basis) over static visuals when presenting molecular representations, confirming that 'dynamic visuals can be more effective than static visuals in fostering molecular understanding about the changes in matter' (p. 1295). Obviously both static and dynamic forms are valuable and can be used to complement each other.

There is convincing evidence from the literature that most student difficulties and misconceptions in chemistry stem from inadequate or inaccurate models of the molecular world (Lijnse, Licht, de Vos, & Waarlo, 1990). In this regard Johnstone & El-Banna (1986) encouraged students to learn new concepts by thinking about them at three levels: the macro, symbolic and micro (molecular) levels. Kozma and Russell (1997) and Bowen (1998) have identified representational competence (the ability of students to transform representations in one form to equivalent representations in another) as an important aspect of successful problem solving in chemistry. In a study to assess students' proficiencies in chemistry upon first entry to tertiary science education in South Africa, Potgieter, Davidowitz, and Blom (2005) designed a test instrument to assess conceptual understanding, logical scientific reasoning, basic mathematical ability, knowledge of subject content and scientific process skills. The analysis revealed serious inadequacies in the ability of students to translate the different modes of representation in chemistry to a molecular level interpretation. They were also unable to translate symbolic presentations (molecular formulae and reaction equations), and everyday or experimental observations into accurate interpretations of events at the molecular level. These findings reflect that teaching in most South African secondary schools is strongly procedural rather than conceptual, and that teachers seldom use schematic presentations in teaching and assessment.

The Use of Chemical Diagrams in Textbooks

The abstract nature of chemistry and the need for the learner to develop a personal understanding of chemical events occurring at the sub-micro level necessitates the use of an extensive range of symbolic representations such as models, problems and analogies. Most of the current learning materials in chemistry make use of the full range of representations. Since this chapter focuses on diagrams, we will consider their use in textbooks because these are likely to be the most widely used resources for students. In an era where multimedia is all pervasive, teachers, textbook authors and instructional designers are aware that being able to switch between the three levels of chemistry is the key to understanding the basic concepts. In his preface to the second edition of his text book, Chemistry: The Molecular Nature of Matter and Change, Silberberg notes that

> Chemistry deals with changes that we observe in the world around us, and with the atomic-scale events that cause them. Throughout the text, discussions team up with illustrations to bring home this central theme. Models are explained at the observable level and then from a close-up, molecular point of view. **To bridge the mind-boggling size gap between these two levels of reality, the first edition (1996) broke new ground in chemical illustration with an art program that juxtaposed the macroscopic and atomic views, and, wherever meaningful, the symbolic view in the form of the balanced equation**. (Silberberg, 2000 pp. xv–xvi, emphasis added).

Examination of elementary general chemistry texts over the last decade reveals an increasing use of multiple representations. An example described as a hallmark by Silberberg is shown in Fig. 8.5.

Figure 8.5 is an example of one of the many three level illustrations which provide a macro and sub-micro view of a process designed to enable students to connect these with each other and with the chemical equation that describes the process in symbols. Several of the ‘end of chapter’ problems in the textbook by Silberberg (2000, 2003, 2006) contain sub-micro representations as do some of the test banks supplied to the instructors. In general, the use of sub-micro diagrams in assessment has developed more slowly than the introduction of the use of the diagrams in text books. For example in the text book, General Chemistry, the chapter on Atoms, Molecules and Ions in the fifth (Ebbing, 1995) and sixth (Ebbing & Gammon, 1999) editions contain no questions with sub-micro representations in contrast to the seventh (Ebbing & Gammon, 2002) and eighth (Ebbing & Gammon, 2005) editions which contain 8 and 10 of these types of questions, respectively.

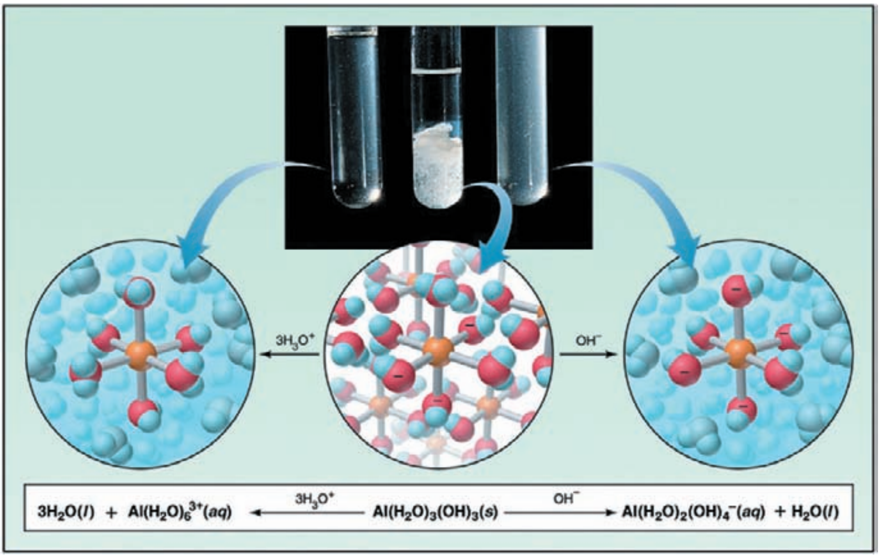


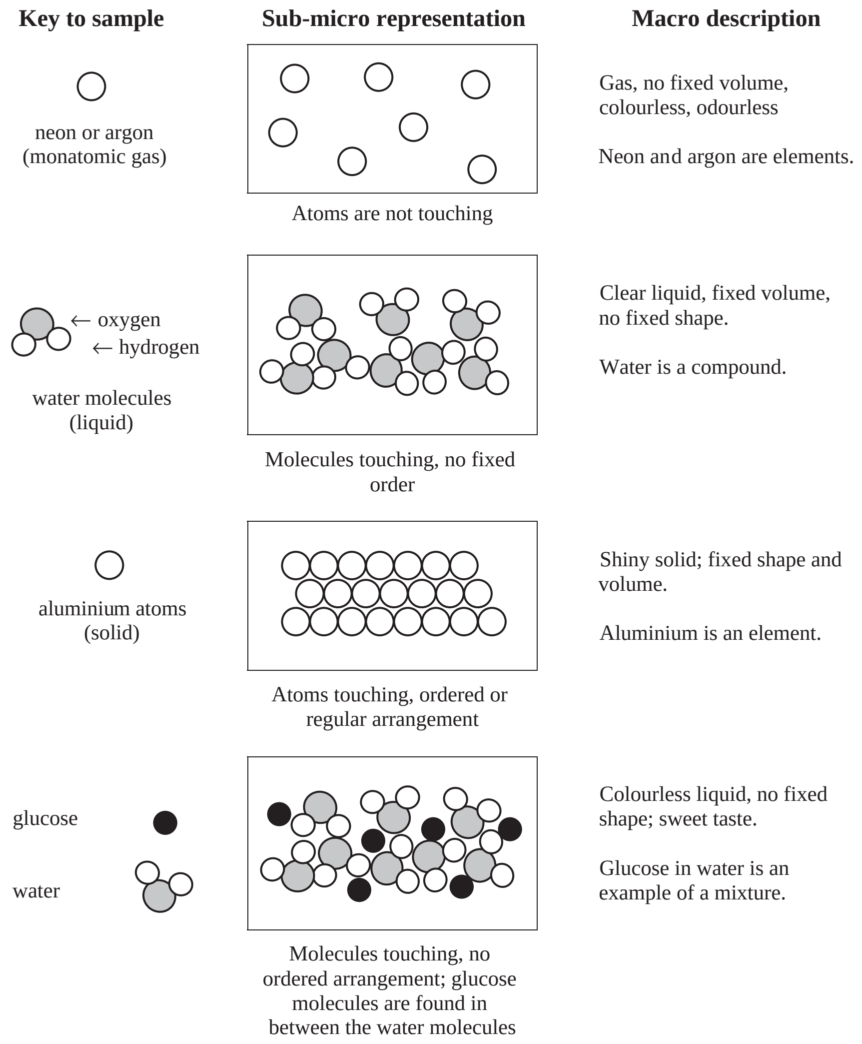
Fig. 8.5 A three level illustration (from M. S. Silberberg, Chemistry: The molecular nature of matter and change, 4th ed., McGraw Hill, 2006, p. xxv, reproduced with permission of The McGraw-Hill Companies)

Using Sub-micro Diagrams Effectively in the Teaching and Learning of Chemistry

This section describes exemplary ways that diagrams of the sub-micro level can be used effectively in the chemistry classroom. Three case studies are presented each identifying a particular conceptual or instructional difficulty and a suggested pedagogical approach that addresses the difficulty.

Case Study 1: Developing skills in interpreting and constructing sub-micro diagrams with students from educationally disadvantaged backgrounds

The conceptual difficulty is a lack of ability to relate the three levels of representation. The strategy uses diagrams to link the sub-micro and the macro level; introduces the sub-micro level before teaching the symbolic conventions; and encourages students to draw and annotate their own drawings of the sub-micro level. It has been suggested that instruction in chemistry should link the three basic representations in chemistry to allow students the opportunity to work with a combination of the macro, sub-micro and symbolic representations (Hinton and Nakhleh, 1999; Johnstone, 1993; Kozma and Russell, 1997; Nurrenbern and Pickering, 1987). Davidowitz teaches chemistry to students identified by the University of Cape Town as being from educationally disadvantaged backgrounds. The programme offers a curriculum that attempts to take account of poor preparation at school by making few assumptions about students' prior knowledge. Research has revealed that students undertaking a first year university course in chemistry are unable to translate between the different levels of representations (Potgieter, Davidowitz, & Blom, 2005). Instruction therefore, focuses on the use of teaching resources such as in Fig. 8.6 which introduces the relationship between the sub-micro and macro level at the start of the course prior to the use of any symbolic representations such as chemical formulae. This strategy intentionally focuses on diagrams at the sub-micro level to provide students with a foundation on which to build ideas such as atoms and molecules, elements, compounds and mixtures. Students are encouraged to engage with these concepts during the tutorial sessions where they work through



Key to sample	Sub-micro representation	Macro description
neon or argon (monatomic gas)	Atoms are not touching	Gas, no fixed volume, colourless, odourless Neon and argon are elements.
← oxygen ← hydrogen water molecules (liquid)	Molecules touching, no fixed order	Clear liquid, fixed volume, no fixed shape. Water is a compound.
aluminium atoms (solid)	Atoms touching, ordered or regular arrangement	Shiny solid; fixed shape and volume. Aluminium is an element.
glucose water	Molecules touching, no ordered arrangement; glucose molecules are found in between the water molecules	Colourless liquid, no fixed shape; sweet taste. Glucose in water is an example of a mixture.

Fig. 8.6 An introduction to conventions commonly used in sub-micro representations

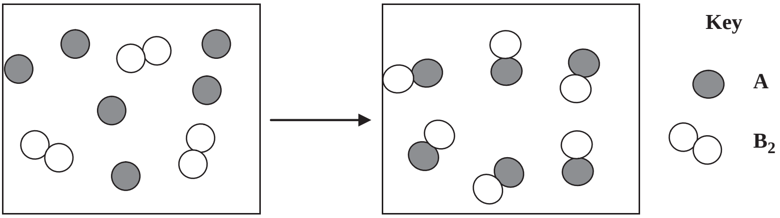


Fig. 8.7 Balancing an equation presented as sub-micro particles

a problem set in which they have to classify representations in terms of both the phase and composition of the substance. They are also presented with samples of substances and asked to draw the corresponding sub-micro representations which present a much greater challenge than simply identifying observable features presented to them.

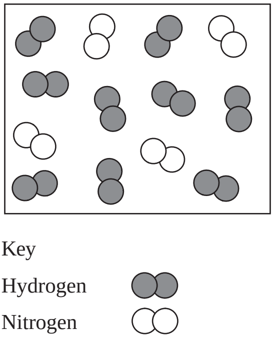
Sub-micro representations are used extensively in teaching the mole concept, stoichiometry, solubility and chemical equilibrium at UCT[1]. Having students draw and annotate chemical diagrams representing chemical phenomena at the sub-micro level can provide some insight into their understanding of chemistry at the macro level. The following examples are typical of the questions used to probe links between the sub-micro and symbolic levels of representations as part of the assessment practice for this course. For example, students were asked to balance the equation shown in Fig. 8.7.

In order to answer this question, students had to identify the product as AB and realise that a balanced equation is always written using the smallest whole numbers ratios for reactants and products. It is pleasing that 63% of the UCT cohort were able to write an appropriate balanced equation compared with the low number of correct responses (15%) reported by Sanger (2005) who used a free response question based on Nurrenbern and Pickering (1987) particulate drawing to evaluate students conceptual understanding of balanced equations and stoichiometric ratios. On the other hand, 22% of the UCT students translated the diagram directly into a chemical equation [$6A + 3B_2 \rightarrow 6AB$] which is similar to a finding by Devetak, Urbancic, Grm, Krnel, and Glazar (2004) who used sub-micro representations as a tool for evaluating students chemical conceptions of chemical equilibrium. Only 6% of the UCT cohort failed to identify the product of this reaction as AB while the remainder made errors involving the stoichiometry of the reaction depicted in Fig. 8.7. These results of the UCT study suggest that allowing students to engage with the material using multiple representations as recommended by Johnstone (1993) and Devetak et al. (2004) has been instrumental in the improved performance of students relative to the study reported by Sanger (2005).

Case Study 2: Sub-micro diagrams as a diagnostic or assessment tool with first year university chemistry students

---

[1] UCT; abbreviation for University of Cape Town, South Africa



Nitrogen, N_2, and hydrogen, H_2, react to form ammonia, NH_3. Consider the mixture of N_2 and H_2 shown in the diagram.

a) Write a balanced equation for this reaction.

b) What is the limiting reagent in this reaction?

c) What is the maximum number of ammonia molecules that can be formed in this chemical reaction?

d) Draw a microscopic representation of the contents of the container after the reaction.

Fig. 8.8 Stoichiometry question based on a sub-micro diagram of the reactants

The instructional difficulty is the student's inability to interpret diagrams; the strategy to address this requires tasks that allow students to interpret the diagrams, relate diagrams to symbolic representations and construct their own diagrams. While some of the questions in text books make use of diagrams to probe conceptual understanding, very few questions require students to construct diagrams. A rare example is shown in Fig. 8.8 (adapted from Brown, LeMay, & Bursten, 2006, p. 111). Assessment procedures used with first year students at UCT during the first semester of 2007 included having students construct diagrams. The questions shown in Figs. 8.8 and 8.9 were used in class tests as formative assessment. To answer the question shown in Fig. 8.8 students had to interpret the diagram which is a more challenging exercise with a higher intellectual demand than the conventional style of question shown in Fig. 8.9. The question shown in Fig. 8.9 can be answered using only the symbolic level of representation.

The following reaction can be used to generate hydrogen gas from methane, CH_4.

$$CH_4(g) + H_2O(g) \rightarrow CO(g) + H_2(g)$$

a) Balance the equation for this reaction.
b) Which is the limiting reagent when 500 g methane reacts with 1300 g water?
c) How many grams of hydrogen can be produced in this reaction?

Fig. 8.9 A typical stoichiometry question on limiting reagents and amount of product formed in a reaction

A summary of the responses to the questions shown in Figs. 8.8 and 8.9 are presented in Table 8.2

Most students demonstrated the ability to translate from the sub-micro to the symbolic level by writing a balanced equation for the reaction in the question shown in Fig. 8.8. In determining the limiting reagent, however, there were a lower number of correct responses than for the question in Fig. 8.9 based on stoichiometry. The difference in performance is even greater for part (c) of both questions

Table 8.2 Summary of responses to questions in Figs. 8.8 and 8.9 (N = 111).

	Question 8% Correct responses	Question 9% Correct responses
Balanced equation	87.5	94.6
Limiting reagent	60.7	98.2
Amount of product formed	37.5	66.7

which essentially involves a determination of the amount of product formed in the reaction. Students are clearly capable of solving stoichiometry problems using an algorithmic-style problem-solving template, Fig. 8.10, while they find it more difficult to do so using sub-micro representations despite the opportunities to practice using the sub-micro representations in tutorials. This finding demonstrates the greater intellectual challenge involved in interpreting the diagrams relative to problems involving only symbols as noted by de Jong and van Driel (2004) and Treagust et al. (2003).

Part (d) of the question in Fig. 8.8 required students to draw a microscopic representation of the contents of the container after the reaction. Just over a quarter of the cohort were able to draw a correct representation of the reaction mixture, namely ammonia and the agent in excess. Almost a fifth of students drew a suitable sub-micro representation of the product molecules but did not include the reagent in excess. About one third of the responses contained a wide variety of incorrect sub-micro representations. Even though students had been taught stoichiometry using sub-micro diagrams such as Fig. 8.4, a number of them (19%) drew diagrams con-

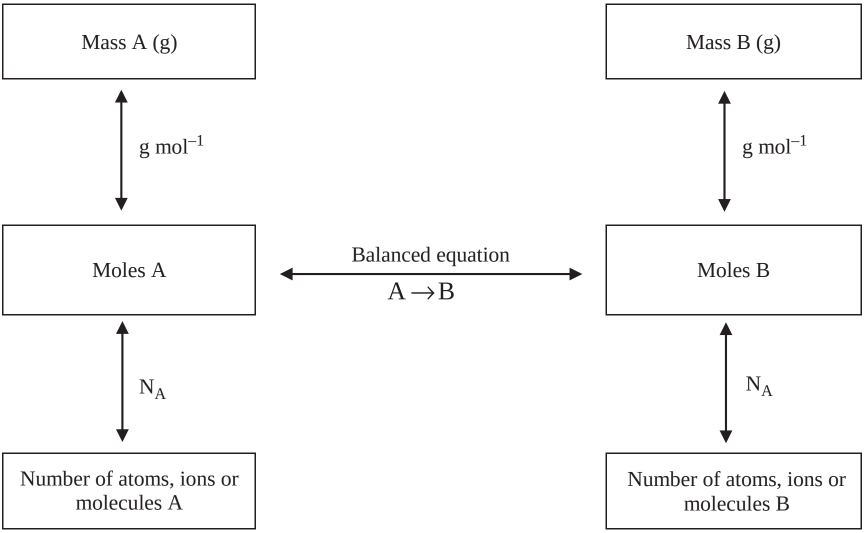


Fig. 8.10 A schematic diagram showing the relationship between mass, moles and the number of particles in a balanced equation

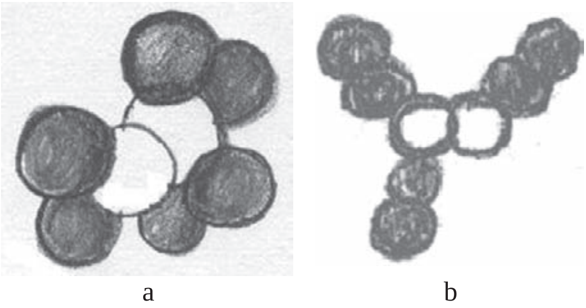


Fig. 8.11 Students' representations of the product of the reaction for question in Fig. 8.8

taining representations consistent with the total number of particles in the product, $2NH_3$. Two commonly occurring examples are shown in Fig. 8.11.

The representation in Fig. 8.11b is similar to one noted by Yarroch (1985) who investigated students' understanding of balancing chemical equations. His results showed that while all the students were able to balance the four chemical equations presented to them, 42% of them could not construct sub-micro diagrams consistent with the symbolic representation of the balanced equation.

Based on their responses to the question in Fig. 8.8 above, the UCT cohort appear to have a better understanding of basic concepts of equations and reactions than students in a study reported by Mulford and Robinson (2002). These authors developed an instrument to investigate common alternative misconceptions about topics found in the first semester of traditional chemistry courses. One of their test items focussed on the understanding of chemical formulae and equations using a sub-micro diagram for the reaction of sulphur and oxygen to produce sulphur trioxide. Students were asked to choose the diagram which showed the results after the mixture had reacted as completely as possible according to the balanced equation shown. The results revealed that the students had a very poor understanding of these key concepts in chemistry with only 11% (pre-test) and 20% (post–test) able to select the correct response, while 60% (50%, post-test) of these students chose representations for S_2O_6 which takes into account only the number of particles in the product. In contrast, 27% of the UCT students could draw the correct products of the reaction and only 19% gave a response based on the number of particles of product in the balanced equation showing the benefit of explicit teaching using sub-micro diagrams.

It could be argued that students may experience difficulties in understanding unfamiliar sub-micro diagrams which may contribute to their poor performance in answering questions as reported in the study by Mulford and Robinson (2002). These authors believe that this is not the case since the diagrams used as distractors for the question on sulphur trioxide were generated by students during the design of their instrument. Interviews with students revealed that none of them had any difficulties in understanding the representations. Hinton and Nakhleh (1999) recommend that not only should educators make explicit use of multiple representations in their classrooms, they should design assessment tasks to reveal students' understanding of ideas around the different levels of representation commonly used in chemistry.

Having students draw their mental model of the product of the reaction reveals misconceptions in understanding of the particulate nature of matter which could then be addressed in the classroom.

Case Study 3: Using diagrams to categorise chemical substances

In this case the instructional difficulty is the student's inability to classify chemicals using diagrams; the teaching strategy encourages students to practice linking to both the macro and sub-micro levels simultaneously, promoting dialogue about the sub-micro level and extending to activities that require higher-order thinking such as predictive tasks.

The categorisation of chemicals into various groupings such as metals, non-metals, elements, compounds and ions, can be confusing for novice students. To address this confusion, a study conducted with first year non-major university chemistry students (Chittleborough & Treagust, 2007), involved interviews about their understanding of various chemical diagrams. The results showed a range of responses largely influenced by the students' chemical background knowledge. For example, one student's response revealed a difficulty transferring from the two-dimensional representation to the three-dimensional as well as understanding the basic difference between elements and compounds. Also her understanding of the subatomic level seemed to be interfering with her understanding at the atomic and molecular level. Another student, who had more chemical background knowledge, discussed his understanding of the representations:

Int.: *Why did you think this one was a compound (referring to Fig. 8.12)*
Student A *The lines represented a bond*.
Int.: *Oh OK and you said the bonds mean a compound and then you looked at it twice, and what did you realise*?
Student A: *It might not be a compound – you don't know – you only know what the lines represent*.
Int.: *Second time you looked at it you said it was an element – why did you say it was an element*?
Student: *Simple because it could be an element or a compound – I'm not too sure*.
Int.: *What do the circles represent*?
Student A: *To me they represent an element*.

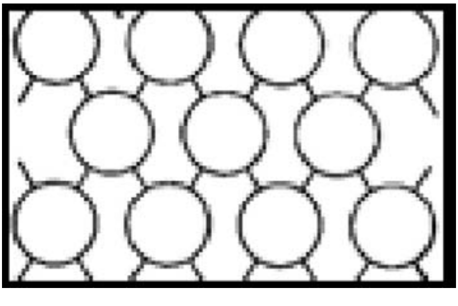


Fig. 8.12 Diagram used in the interview with students

This student equated lines with bonds, and he associated bonds with compounds, forgetting that elements can also have bonds. He also equated circles with elements not atoms. Lastly another student, who was able to distinguish the reality from the representation, did not relate the two at all.

Int.: *How do you visualize the beaker with the ions mixing/dissolving in with the water*?

Student B: *I honestly have no idea when it comes to things like that. Like I can't visualize the difference between having H_2O written down on paper and then looking at it. It doesn't look the same, it's nothing*.

Int.: *Yeah, So the real thing is so remote from the symbolic that . . .*

Student B: *It's unbelievable*.

This student had no chemistry background knowledge and did not think about matter in a particulate way. This student did not link to the macro and sub-micro levels simultaneously but used them independently. These results reveal difficulties that some students have in identifying the significant components of chemical diagrams and the conventional symbolism that are used. Consequently, assumptions commonly made by instructors with respect to students' abilities to interpret chemical diagrams should be questioned.

Implications for Teaching

Research and practice suggest that teaching approaches may enhance the effectiveness of using diagrams in teaching chemistry. To achieve this outcome, teachers can:

- Use diagrams carefully and explicitly
- Be selective in their choice of diagrams
- Use multiple chemical diagrams, especially those that incorporate all three levels
- Respond to the visual capabilities of students e.g. visual learners
- Respond to the availability of enhanced visuals resulting from new technologies
- Use diagrams to discuss processes which cannot be seen with the naked eye
- Familiarise students with the conventions used in diagrams
- Require students to construct diagrams of the sub-micro level
- Allow students to practice interpreting multiple representations
- Provide scaffolding to develop competence
- Use diagrams for predicting and testing
- Promote metavisualisation skills
- Make no assumptions about students' ability to interpret diagrams of the sub-micro level

The information presented suggests that there is a need for strategies that promote active interaction with diagrams. Consistent with a constructivist approach, these suggested strategies require students to demonstrate their understanding and receive feedback. In this way, the diagram becomes an active tool rather than a passive tool for learning.

Students' use of diagrams is frequently limited by their lack of chemical knowledge, their lack of ability to attend to the detail of the diagram and their lack of ability to use chemical terminology accurately, evidenced by the incorrect use of chemical phrases and misuse of everyday language. There are three important facts that need to be understood in order to gain a better understanding of the sub-micro level:

- Many symbolic representations such as diagrams are used to help understand the unseen sub-micro level of chemical representation of matter.
- The symbolic level of chemical matter is a representation, while the sub-micro level of chemical matter is real.
- Accuracy and detail provided by multiple symbolic representations are sources of information to understand the sub-micro level of chemical representation of matter.

These three aspects are illustrated in Fig. 8.5 which depicts a representation of the sub-micro level, has links to the macroscopic level to make the representation real and to provide a context, and presents angles, sizes and colours for accurate detail of the representation. Based on these three important facts, teachers and instructors must create opportunities for their students to learn to interpret sub-micro diagrams which are a feature of modern learning materials. As noted earlier, chemical literacy includes being able to interpret and use chemical diagrams (Gabel, 1999; Johnstone, 1993; Treagust & Chittleborough, 2001) thus this skill should be taught and assessed. Instead of simply assuming that students will absorb the information presented to them in sub-micro diagrams, teachers should 'add value' by guiding them to a full understanding of this potentially very powerful tool. The conventions used in the sub-micro representations should be taught explicitly.

Assessment in chemistry commonly emphasises numerically based problems, so reference to the sub-micro level can be marginalised or considered to be less important. An alternative approach is to provide students with greater exposure to a variety of chemical diagrams of different formats. Having students construct their own diagrams has been shown to be effective in revealing their understanding of particular concepts. Diagrams are a valuable teaching tool but should not be used in isolation since research has recommended the need to link sub-micro diagrams to other levels of representations in chemistry.

References

Andersson, B. (1990). Pupils' conceptions of matter and its transformations (age 12–16). *Studies in Science Education, 18*, 53–85.

Ardac, D., & Akaygun, S. (2004). Effectiveness of multi-media-based instruction that emphasizes molecular representations on students' understanding of chemical change. *Journal of Research in Science Teaching, 41*(4), 317–337.

Ardac, D., & Akaygun, S. (2005). Using static and dynamic visuals to represent chemical change at molecular level. *International Journal of Science Education, 27*(11), 1269–1298.

Ben-Zvi, R., Eylon, B.-S., & Silberstein, J. (1987). Students' visualisation of a chemical reaction. *Education in chemistry, 24*(109), 117–120.

Bowen, C. W. (1998). Item design considerations for computer-based testing of student learning in chemistry. *Journal of Chemical Education, 75*(9), 1172–1175.

Brown, T. L., LeMay, H. E., & Bursten, B. E. (2006). *Chemistry: The central science* (10th ed.). New Jersey, Pearson: Prentice Hall.

Bucat, R. (2004). Pedagogical content knowledge as away forward: Applied research in chemcitry education. *Chemistry Education Research and Practice, 5*(3), 215–228.

Chittleborough, G. D., & Treagust, D. F. (2007). The modelling ability of non-major chemistry students and their understanding of the sub-microscopic level. *Chemistry Education: Research and Practice, 8*(3), 274–292.

Chittleborough, G. D., & Treagust, D. F. (2008). Correct interpretation of chemical diagrams requires transforming from one level of representation to another. *Research in Science Education, 38*(4), 463–482.

Collins, A., & Gentner, D. (1987). How people construct mental models. In D. Holland & N. Quinn (Eds.), *Cultural models in language and thought* (Vol. 1, pp. 243–265). New York: University of Cambridge.

de Jong, O., & van Driel, J. (2004). Exploring the development of student teachers' PCK of the multiple meanings of chemistry topics. *International Journal of Science and Mathematics Education, 2*, 477–491.

Devetak, I., Urbancic, K., Grm, W., Krnel, D., & Glazar, S. (2004). Submicroscopic representations as a tool for evaluating students chemical conceptions. *Acta Chimica Slovenica, 51*, 799–814.

Ebbing, D. D. (1995). *General chemistry* (5th ed.). New York: Houghton Mifflin Company.

Ebbing, D. D., & Gammon, D. S. (1999). *General chemistry* (6th ed.). New York: Houghton Mifflin Company.

Ebbing, D. D., & Gammon, D. S. (2002). *General chemistry* (7th ed.). New York: Houghton Mifflin Company.

Ebbing, D. D., & Gammon, D. S. (2005). *General chemistry* (8th ed.). New York: Houghton Mifflin Company.

Fiorea, S. M., Cuevasa, H. M., & Oser, R. L. (2003). A picture is worth a thousand connections: The facilitative effects of diagrams on mental model development and task performance. *Computers in Human Behavior, 19*(2), 185–199.

Gabel, D. L. (1993). Use of the particulate nature of matter in developing conceptual understanding. *Journal of Chemical Education, 70*(3), 193–194.

Gabel, D. L. (1998). The complexity of chemistry and implications for teaching. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 233–248). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Gabel, D. L. (1999). Improving teaching and learning through chemistry education research: A look to the future. *Journal of Chemical Education, 76*(4), 548–554.

Gabel, D. L., Briner, D., & Haines, D. (1992). Modelling with magnets: A unified approach to chemistry problem solving. *The Science Teacher, 59*(3), 58–63.

Garnett, P. J., Garnett, P. J., & Hackling, M. W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education, 25*, 69–95.

Gilbert, J. K. (2005). Visualization: A metacognitive skill in science education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 9–27). Dordrecht, the Netherlands: Springer.

Giordan, A. (1991). The importance of modelling in the teaching and popularisation of science. *Impact of Science on Society, 164*, 321–338.

Gobert, J. D., & Clement, J. J. (1999). Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics. *Journal of Research in Science Teaching, 36*(1), 39–53.

Hinton, M. E., & Nakhleh, M. B. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions. *The Chemical Educator, 4*(4), 1–29.

Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemical Education, 70*(9), 701–705.

Johnstone, A. H. (2000). Teaching of chemistry – logical or psychological. *Chemistry Education: Research and Practice in Europe, 1*(1), 9–15.

Johnstone, A. H., & El-Banna, H. (1986). Capacities, demands and processes – A predictive model for science education in chemistry. *Education in Chemistry, 23*, 80–84.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*(9), 949–968.

Kozma, R. B., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In J. K. Gilbert (Ed.), *Visualization in Science Education* (pp. 121–146). Dordrecht, the Netherlands: Springer.

Krajcik, J. S. (1991). Developing students' understanding of chemical concepts. In S. M. Glynn, R. H. Yeany, & B. K. Britton (Eds.), *The psychology of learning science* (pp. 117–147). Hillsdale, NJ: Lawrence Erlbaum Associates.

Krnel, D., Watson, R., & Glazar, S. A. (1998). Survey of research related to the development of the concept of 'matter'. *International Journal of Science Education, 20*(3), 257–289.

Lijnse, P. L., Licht, P., de Vos, W., & Waarlo, A. J. (1990). *Relating macroscopic phenomena to microscopic particles* (Ed.), Utrecht, Holland: CD-β Press, pp. 283–293.

Mayer, R. (2002). Cognitive theory and the design of multimedia instruction *New Directions for Teaching and Learning, 89*, 55–71.

Mayer, R. (2003). The promise of multimedia learning: using the same instructional design methods across different media. *Learning and Instruction, 13*(2), 125–139.

Mulford, D. R., & Robinson, W. R. (2002). An inventory for alternate conceptions among first-semester general chemistry students. *Journal of Chemical Education, 79*(6), 739–744.

Nelson, P. G. (2002). Teaching chemistry progressively: From substances, to atoms and molecules, to electrons and nuclei. *Chemistry Education: Research and Practice in Europe, 3*(2), 215–228.

Nicoll, G. (2003). A qualitative investigation of undergraduate chemistry students' macroscopic interpretations of the submicroscopic structure of molecules. *Journal of Chemical Education, 80*(2), 205–213.

Nurrenbern, S. C., & Pickering, M. (1987). Concept learning versus problem solving: Is there a difference? *Journal of Chemical Education, 64*(6), 508–510.

Onwu, G., & Randall, E. (2006). Some aspects of students' understanding of a representational model of the particulate nature of chemistry in three different countries. *Chemistry Education: Research and Practice, 7*(4), 226–239.

Potgieter, M., Davidowitz, B., & Blom, B. (2005). Chemical concepts inventory of first year students at two tertiary institutions in South Africa. In *the conference proceedings of the 13th Annual Conference Southern African Association of Research in Mathematics, Science and Technology Education*. Namibia, pp. 664–675.

Sanger, M. J. (2000). Using particulate drawings to determine and improve students;' conceptions of pure substances and mixtures. *Journal of Chemical Education, 77*(6), 762–766.

Sanger, M. J. (2005). Evaluating students' conceptual understanding of balanced equations and stoichiometric ratios using a particulate drawing. *Journal of Chemical Education, 82*(1),131–134.

Sanger, M. J., Campbell, E., Felker, J., & Spencer, C. (2007). Concept learning versus problem solving: Does particle motion have an effect? *Journal of Chemical Education, 84*(5), 875–879.

Sanger, M. J., & Phelps, A. J. (2007). What are students thinking when they pick their answer? A content analysis of students' explanations of gas properties. *Journal of Chemical Education, 84*(5), 870–874.

Silberberg, M. S. (2000). *Chemistry: The molecular nature of matter and change* (2nd ed.). Boston: McGraw Hill.

Silberberg, M. S. (2003). *Chemistry: The molecular nature of matter and change* (3rd ed.). Boston: McGraw Hill.

Silberberg, M. S. (2006). *Chemistry: The molecular nature of matter and change* (4th ed.). Boston: McGraw Hill.

Stevens, M. G., Owens, C., & Wuhrer, R. (2002). Nanotechnology in society. *Australian Science Teachers' Journal, 48*(3), 22–27.

Tasker, R., & Dalton, R. (2006). Research into practice: Visualization of the molecular world using animations. *Chemistry Education Research and Practice, 7*(2), 141–159.

Treagust, D. F., & Chittleborough, G. D. (2001). Chemistry: A matter of understanding representations. In J. Brophy (Ed.), *Subject-specific instructional methods and activities* (Vol. 8, pp. 239–267). Oxford: Elsevier Science Ltd.

Treagust, D. F., Chittleborough, G. D., & Mamiala, T. L. (2003). The role of sub-microscopic and symbolic representations in chemical explanations. *International Journal of Science Education, 25*(11), 1353–1369.

Velázquez-Marcano, A., Williamson, V., Askenazi, G., Tasker, R., & Williamson, K. (2004). The use of video demonstrations and particulate animation in general chemistry. *Journal of Science Education and Technology, 13*(3), 315–323.

Wright, T. (2003). Images of atoms. *Australian Science Teachers Journal, 491*, 18–24.

Yarroch, W. L. (1985). Students' understanding of chemical equation balancing *Journal of Research in Science Teaching, 22*, 449–459.

Zare, R. (2002). Visualizing chemistry, journal of chemical education. *Journal of Chemical Education, 79*(11), 1290–1291.

Part III
Classroom Solutions to the Challenges Posed by the Triplet Relationship

This section consists of five papers, each taking a different approach in addressing the challenges that are posed by teaching and learning about the triplet relationship.

The first approach, taken by Pilot, Meijer and Bulte, in Chapter III, is to break up the challenges into smaller segments and to ensure that meeting those challenges is seen to be worthwhile by students. Building on the socio-cultural theory of knowledge construction, with its emphasis on access to authentic tasks under the guidance of experts, they interviewed expert chemists about how they would go about making unbreakable crockery, gluten-free bread and a bullet-proof vest, respectively. An analysis of the interviews showed that the experts used a series of intermediate representations on moving between the sub-micro and macro. On the basis of this, they designed a series of classroom activities based on these three exemplar tasks that caused the students to use such intermediate representations. The conclusion drawn is both radical and very worthwhile: the cognitive gap between the macro and the submicro can be bridged.

In Chapter 10, Scheffel, Brockmeier and Parchmann, look at the value of the study of the history of chemistry in chemical education, focusing especially on the insights the approach affords to understand the macro/submicro/symbolic links. They give concise accounts of the historical development of five major themes in chemistry (the particulate nature of matter, structure–property relations, ionic bonding, covalent bonding and organic chemistry, macromolecular chemistry), focusing on how submicro and symbolic representations and explanations evolved, and review the educational research literature on students' understanding of these themes. Their thesis is that knowledge of how chemistry developed historically can support students in developing their ideas from those seen as important in historical episodes. They also discuss some ideas of how this can be done in the classroom and give some preliminary results of their implementation.

In contrast,Chapter 11 looks at the very recent introduction of computer-based multimedia technologies into chemical education as a way of forging macro/submicro/symbolic links. Chiu and Wu discuss the value of such approaches as, respectively, a modelling tool, a learning tool, an assessment tool and an instructional tool. Their thesis is given added weight by the inclusion of results from classroom development and evaluation projects.

The key to all the approaches to forging macro/sub-micro/symbolic links is the act of modelling i.e. that of producing internal representations of a phenomenon and the associated external representations of those. Underlying the process of modelling is the exercise of visualization: mentally acting on an internal representation. In Chapter 12, Justi, Gilbert and Ferreira, present a 'model of modelling': a framework of actions and cognition associated with the production and use of an internal representation. Taking the case study of 'chemical equilibrium', they show how high school children engage in the act of modelling and, in particular, how the skills of visualization are deployed and developed.

If modelling is the core mental activity in developing an understanding of the triplet relationship, then providing a situation in which students and teachers feel it to be worthwhile is equally important. In Chapter 13, Savec, Sajovi, and Grm, drawing on a national project in Slovenia, present a case study of the use of a context-based approach to course design. They give an account of the development and implementation in schools of a teaching unit on 'chemical reactions' that is context-based, showing that it was very effective in enabling students to learn the key ideas of the topic. Of equal importance is the fact that the whole project was conducted on an 'action research' basis, with classroom teachers centrally involved in all aspects of the project. These teachers kept 'reflective diaries' as the project was implemented, revealing a great deal about how this project, typical in many ways of innovations concerned with the triplet relationship, was adopted and adapted in schools.

Chapter 9
Structure–Property Relations Between Macro and Micro Representations: Relevant Meso-levels in Authentic Tasks

Marijn R. Meijer, Astrid M.W. Bulte and Albert Pilot

Abstract In chemistry education, micro–macro thinking using structure–property relations is considered as a key conceptual area for students. However, it is difficult but challenging for students and teachers. In this chapter, we have redefined this domain in terms of a coherent set of philosophical, substantive and pedagogical substructures. Starting from the philosophy that chemistry should be considered as a human activity, scientific and technological developments are interrelated with issues in society and part of our cultures. In many communities of practice in society, knowledge is regarded as a tool necessary for performing the activities of those practices. Learning chemistry can be seen as participation in relevant social practices. Within this vision, we have selected tasks belonging to authentic chemical practices in which structure–property relations were explored in different subdomains (biochemistry, inorganic material science and organic polymeric material science). Within the substantive substructure, meso-structures are essential to iterate between the macro- and the sub-microscopic level. Interrelating structure–property relations connect student learning of these chemical concepts to the contexts of their everyday lives and to contemporary science and technological issues. Using this way of macro–micro thinking, two units for teaching structure–property relations were designed. These units focus on macro–micro thinking with steps in between: what we have termed 'meso-levels'. The results of the conceptual analysis of structure – property relations and how these relations are used in macro–micro thinking are discussed. We also present a first exploration of students' learning of authentic tasks, focusing on their conceptual development.

Reconsidering the Content of the Domain of Macro–Micro Thinking

Micro–macro thinking using structure–property relations is considered as a key conceptual area in the domain of chemistry. This area is concerned with the understanding of properties and transformations of materials, for which chemists

---

M.R. Meijer (✉)
Universiteit Utrecht, Utrecht, The Netherlands
e-mail: m.r.meijer@phys.uu.nl

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_10,

construct models for investigating known and new substances and their transformations (Justi & Gilbert, 2002). For some tasks these models imply evident relations between macroscopic properties (boiling point, solubility) and sub-microscopic models like molecules or atoms. However, for many other tasks in contemporary science and technology, the relevant structures appear to be at other levels than the sub-microscopic level. In many contemporary authentic tasks, properties of materials are explained and predicted by 'models' that do not immediately relate to structures at a molecular or atomic level (e.g. nanotechnology, genomics and micro-structured materials). Empirical data on the functional relevance in chemical expertise for such tasks and the scales of these intermediate levels will be discussed in this paper.

Learning to relate macroscopic phenomena to sub-microscopic models is perceived as difficult. When trying to acquire knowledge about such models, students have difficulty understanding the relation between the phenomena and their representation. The step from the level of macroscopic phenomena to the lowest sub-microscopic representations is huge. Often it implies a number of relations and steps that are not described explicitly in textbooks (Han & Roth, 2006). Breaking up the macro–micro jump into smaller parts could make the cognitive load less demanding for students. Intermediate (meso) levels might be functional in the teaching and learning of macro–micro thinking. Within this respect, Millar (1990) states that

> 'we do not have to go straight from the observable to the atomic/molecular level; there are steps in between' and 'that learning necessarily proceeds via a series of intermediate steps, or 'models' . . .' (see also Besson & Viennot, 2004 for physics education).

We therefore focus on a system of intermediate 'meso' levels that manifest when studying structures and properties of macroscopic objects and materials, such as foods, designed everyday artefacts and cloths (cf. Aguilera, 2006; Cussler & Moggridge, 2001; Walstra, 2003). For example, weaving patterns of threads comprise fibres that have amorphous and crystalline filaments. These structures are examples of intermediate meso-structures that relate to properties, such as the strength of a thread, the flexibility of textile and the stiffness of cloths. Properties and structures can be attributed to the different scales of this system. Within such a conceptual schema, the meso levels should link macroscopic phenomena to microscopic models in a step-wise thinking process using the structure, properties and their interrelations at the different levels.

Although in the context of everyday life and in contemporary science and technology, new materials and structured foods have come into focus, the learning of how to relate the sub-microscopic world of chemistry to macroscopic phenomena of these (bio)materials has not become a substantial part of the chemistry curriculum in schools. Instead, many school chemistry curricula have a dominant focus on corpuscular theories that pretend to offer students a general perspective for interpreting macroscopic phenomena. Additionally, student learning is organised by textbooks-with-exemplars where dealing with the symbolic representations may lead to 'plugging in numbers' (see Van Berkel, Pilot, & Bulte, in press). Van Berkel et al. have analysed how a curriculum consists of three substructures: a substantive,

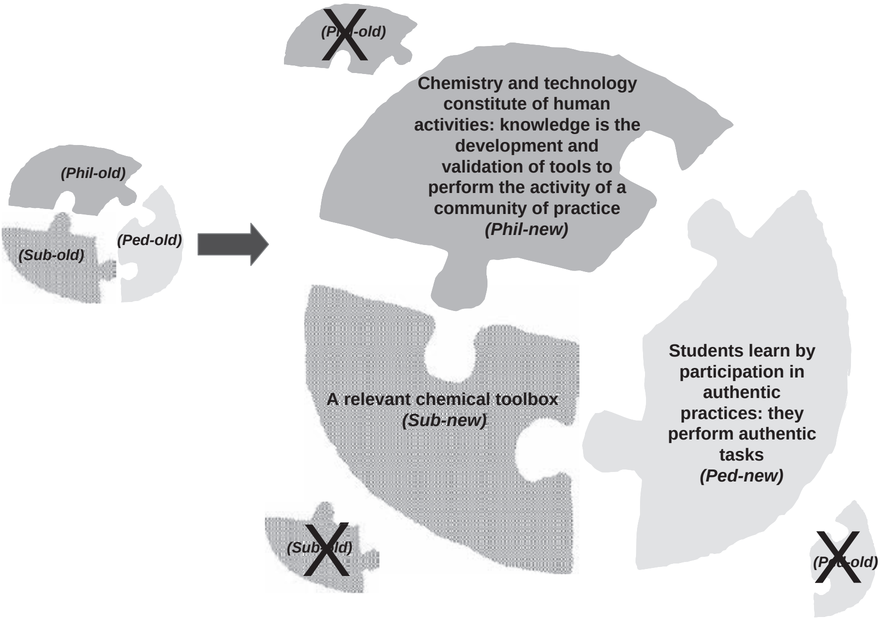


Fig. 9.1 For a new coherent relationship between philosophy, pedagogy and scientific content; the three conventional substructures should be simultaneously replaced by three new substructures in a coordinated way

a philosophical and a pedagogical substructure (Schwab, 1964, 1978; Fig. 9.1). Van Berkel et al. conclude that a coordinated replacement of all three substructures, including the reconceptualisation of the substantive substructure, is necessary if school chemistry is to address new scientific and technological developments and to deal with a better pedagogical approach than the dominant *micro–macro thinking* with its strong corpuscular basis. Students' thinking should start with macroscopic phenomena; it implies the search for those models that are applicable when manipulating and understanding properties of materials. We therefore identify this type of thinking as *macro–micro thinking* (in stead of micro–macro thinking). The meaningful learning of macro–micro thinking in a relevant context (Gilbert, 2006; Pilot & Bulte, 2006) thus implies a new coherent vision on the curriculum's philosophy; the curriculum content and its pedagogy (see also Fig. 9.1).

Towards a New Vision of Macro–Micro Thinking

Philosophical Substructure

A key starting point for learning chemistry is to consider chemistry as a human activity. Scientific and technological developments are interrelated with society and part of our cultures. In society, in many communities of practice (Wenger, 1998), knowledge is seen as a tool necessary for performing the activities of those practices. A chemical and technological perspective offers a view on the materials and substances we use, that we are made of and that constitute our material world. This enables us to understand certain macroscopic phenomena and offers us possibilities to technologically improve our environment, and reconsider their ethical implications. The way communities discover knowledge as tools and define these tools as valid and applicable constitutes the philosophical structure of the community. The process by means of which representative participants of relevant scientific and technological communities deal with material science, develop and validate knowledge, is related to the selection and analysis of authentic tasks.

Substantive Substructure (Sub)

The content of a curriculum must be functional when dealing with societal activities: necessary chemical concepts, skills and attitudes with respect to macro–micro thinking must be included. This can be derived from representative authentic tasks. The content of the curriculum should be considered as a *chemical toolbox*. The traditional content of the present chemistry curriculum, such as the structure of atoms, ionic theory, fundamental acid–base calculations, are not necessarily part of the chemical toolbox when addressing chemical and technological tasks. The validity of the toolbox (philosophical substructure) is determined by the representative practices and tasks related to chemistry (cf. ‘need-to-know’ principle in context-based approaches).

Pedagogical Design (Ped)

As Schwab explained (see Van Berkel et al., in press), the choice of a pedagogical approach is not independent of the chosen philosophical and substantive substructure of a curriculum. A philosophical and a substantive substructure together imply and determine a pedagogical substructure. The pedagogical substructure must be brought in agreement with appropriate principles of teaching and learning. Students should construct knowledge through their interactions with participants of relevant communities of practice in material science. Fundamental to this perspective are features of *active construction, situated cognition, community* and*discourse* (Anderson, Greeno, Reder, & Simon, 2000; Kelly, 2007; Rivet, Slinger, Schneider, Krajick, & Marx, 2000). Through discourse, students should become familiarised with the common language of chemistry as a perspective on the world. The design of learning tasks must stimulate students to realise that *they* come to *need* a chemical perspective. A new vision on chemistry education should explicitly aim at putting students in a position where they themselves *want* to extend their conceptual network (Lijnse & Klaassen, 2004). Novices learn by participation in a community where they learn the expert's personal knowledge, intellectual passion, faith, trust, tacit understanding, and methodological rules embodied in scientific and technological practices (Jacobs, 2000; Polanyi, 1958). It is by the expert's inspiration that students may enter their zone of proximal development (Vygotsky, 1986).

In sum, this new vision on the learning of macro–micro thinking consists of a coherent construct of the three following substructures (see also Fig. 9.1):

- *Philosophical substructure*: the argumentation about how content is defined as valid and applicable in chemically relevant social (communities of) practice;
- *Substantive substructure*: a chemical toolbox for the selected practices with macroscopic phenomena as relevant 'properties' as a starting point; the 'toolbox' consists of those representations identified as 'structures', relevant features of the structures and explicit relations between 'structures' and 'properties'.
- *Pedagogical substructure*: the way students may come to be participant of the selected practices.

In this vision, the conceptual analysis within the substantive substructure for macro–micro thinking is thus highly dependent on the selection of chemically relevant practices within which authentic tasks are situated. These tasks thus need to be selected on criteria consistent with the adopted vision on macro–micro thinking as described above. Firstly, tasks need to be situated in chemically representative practices (*Phil*). Secondly, a task should be selected such that it can bring students to within its zone of proximal development (*Ped*; Vgkotsky, 1986). In this way students can be expected to be willing to extend their conceptual network (cf. Prins et al., 2008). Thirdly, the exemplary tasks should cover a wide range of the domains of contemporary chemistry and technology in which macro–micro thinking plays a central role (*Sub*).

Consequently we have selected three tasks in three relevant domains of chemistry and (material or food) technology which are expected to be within the zone of proximal development for students:

- the development of gluten-free bread (domain of biochemistry);
- the design of unbreakable ceramic crockery (domain of inorganic material science); and
- the design of a flexible bullet-proof jacket (domain of polymeric organic material science).

With respect to the nature of the tasks, we chose a developmental or a design task because we expected that such a behavioural environment (Gilbert, 2006) is closer to the lives of students. Besides, these tasks may offer opportunities for experimentation and hands-on activities in classrooms, when such tasks are meant as contexts for learning macro–micro thinking.

We therefore started to explore the use of relations between representations of structure and properties of materials using these context-based authentic tasks as a starting point (cf. Bulte, Westbroek, de Jong, & Pilot, 2006). We aimed to reconceptualise the content of macro–micro thinking and structure–property relations, to make these structure–property relations explicit to connect macroscopic phenomena with microscopic representations in a new conceptual schema, which is appropriate for addressing contemporary chemical and technological tasks. Relevant documents (research articles, scientific textbooks, etc.) were analysed. Subsequently we selected experts for three tasks in representative authentic social chemical and technological practices. When consulting and interviewing the experts, they were asked to think aloud while addressing the tasks. By analysing the transcripts of interviews, we analysed the outcomes in terms of the substantive substructure of a curriculum, which should be in accordance with the chosen philosophy. This analysis forms the first part of this chapter.

In the second part of this chapter, we present to what extent students can learn to work with the new content of the activities closely related to the authentic practice. This is a further development of the pedagogical substructure that needs to be coherent with the curriculum's philosophy and its content. We therefore have used the same authentic tasks as were used for deriving the new content. By doing so, we maintained the coherency between the socio-scientific activity (*Phil*) and the content that was necessary to address the tasks (*Sub*). We investigated how students can be meaningfully involved in such authentic activities and come to see the relevance to explain and predict properties of materials (*Sub*). This should ensure an emerging coherency with the pedagogic substructure (*Ped*) of the curriculum. Therefore, the planning of an appropriate teaching and learning sequence should help students to *meaningfully* learn (*Ped*) to use structure–property relations as links between the different meso-levels. In this way, the students should see the point of why they should eventually use molecular and atomic structures at the sub-microscopic level. When students enter their zones of proximal development, the designed units should productively build on the belief system of prior knowledge and notions of students on how to handle this task and facilitate the expansion of their knowledge along their activities while descending from the macro to the micro level.

Substantive Substructure of Authentic Socio-scientific Activity

After a description of each task, we present the results of the document analysis and a summary of the experts' consultation. Interviews were mainly categorised on 'structure', 'property' and their interrelations (Meijer, Bulte, & Pilot, 2005). This section starts with a more extensive description for the task about crockery. The outcomes for the two other tasks are more briefly described. Subsequently, the outcomes of the analysis of the two other tasks are summarised and generalised.

The Analysis of the Design of Ceramic Crockery

Crockery preferably is made from ceramic materials, although it is brittle and can break rather easily. Properties of ceramics, such as resistance to absorb flavours and low heat conductivity, however, are superior compared to metals and plastics. Therefore, we defined a task to design crockery with improved mechanical strength.

Textbooks about inorganic material science report that the strength of porcelain cups is determined by the avoidance of crack growth. This can be achieved by using grain particles with very small diameter, by addition of grain-growth inhibitors, and by processing the material at high sinter temperatures. Changing these factors results in a densely compacted (low porosity) phase (with a low content of silica) which results in a limited crack growth. Such ceramic material will not break easily.

The expert tried to optimise the design of unbreakable crockery. First he wanted to find reasons for using ceramic as the main material in terms of desired properties. From this first step, he concluded that ceramic had some advantages over metals or composites. The expert made a sharp distinction between intrinsic and extrinsic properties. The choice of type of ceramics was not relevant because the desired properties are extrinsically determined. Thus relevant properties cannot be much influenced by the difference in bonding strength due to the different types of ions of the material. Consequently, the properties of ceramic crockery are not much influenced by the actual choice of ceramic material. Because of this, the expert did not include the ionic structure in his reasoning. When he was asked why he did not use this sub-microscopic level, he explained; 'it was not necessary because this [the desired property] is not undergoing influences at atomic level at all'.

Relevant information taken from the documents was combined with the expert's consultation. The verbal utterances combined with relevant representations of structures in textbooks, papers and journals could be combined into a system of structures, properties and their interrelation. The results are summarised in Fig. 9.2. Six meso levels were relevant to address the task. At a meso level of (10^{-3} m) the

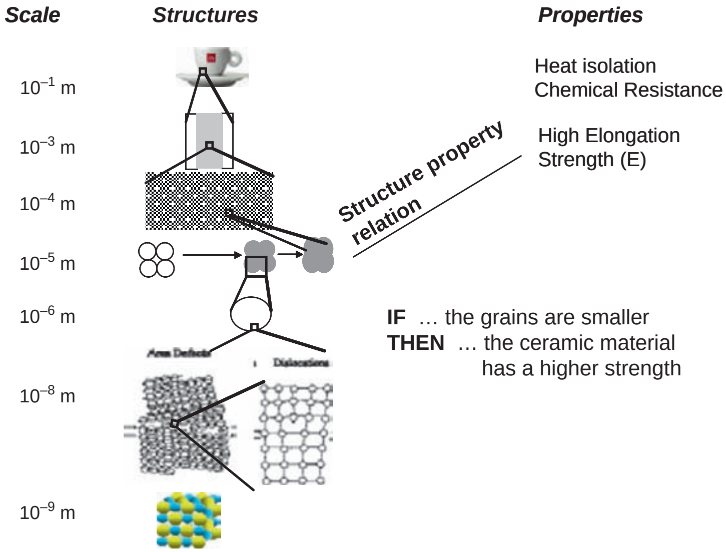


Fig. 9.2 Conceptual schema of the development of an unbreakable cup. Examples of structure–property relations are marked as *lines*.

ceramics is coated with a glaze. The ceramic is a porous material (10^{-4} m) which is a result of the sintering process (10^{-5} m). In this sintering process, grain particles (10^{-6} m) form necks. A particle is built up from amorphous and crystalline phases (10^{-7} m). Between these phases defects or regular parts (10^{-8} m) are found which are built up from ions (10^{-9} m).

The expert did not order his reasoning in a fixed manner between macro and micro level. This is expressed by reorientations (starting again at another level) and iterations (switched between levels) of the expert, when he was weighing two different alternative strategies (A and B). Examples of this type of reasoning are:

Re-orientation	– What must I do? I can do two things. Keep defects small, if I want to keep defects small I must start off with small particles. – Route A is to keep the defect small. Made small by impregnated. Two ways. Then you get route B that's the strain.
Iteration	– All right, then we get ceramics . . . And ceramic is essentially brittle. – And I can think of impregnating the defects. If I make them large, yes exactly, that would be the alternative.

When comparing the document analysis with the expert's consultation, two important differences come to the fore: (1) the generalisation of the expert's thinking process, and (2) less focus on the micro-level by the expert. The expert started with a much broader set of materials (metals, polymers and ceramics). Then the expert wanted to find a clear argumentation for using ceramic as a main material. This makes the approach of the expert more general. Secondly, the expert had no reason to use detailed information about the chemical components. Most desired properties were only a result of microstructures (at meso level) and not of the (pure) ionic substances. This implies that the expert used his knowledge about general properties of this class of materials (ceramic). Documents, however, include the frequent use of chemical information about several types of ceramics, the influence of whiteners, grain growth inhibitors, and the amount of silica and mullite in porcelain. For the expert, these details were not necessary to address the task. The expert's reasoning is more generally applicable. Figure 9.2 represents the combined conceptual analysis of the design of unbreakable crockery taken from document analysis and the expert's reasoning.

The expert's use of structure property relations can be expressed in 'if . . . then . . .' clauses (Fig. 9.2) as 'rules' to connect properties to structures. In such relations structures are assigned to a 'smaller' scale compared to properties. Examples are: 'If you have particles with a small diameter (scale = 10^{-6} m), then the connection is less strong (scale = 10^{-3} m)', and 'If I observe a high value of shrinkage (scale = 10^{-5}), then it may have resulted in a low porosity (scale = 10^{-4} m)'. Ten structure – property relations were identified, but only one structure–structure relation was found: 'If I keep defects [structure] small then I must start with particles with a small diameter [structure]'. This sentence can be interpreted as a construction from two implicit structure–property relations between the diameter of the grains and strength and between defects and strength. For example, porosity [property] means less holes and pores between the sintered particles [structure], which results in a decrease of possible path ways for crack formation [structure]. A limitation of crack forming results in higher strength [property]. Connecting the properties with a scale leads to the conclusion that properties are connected to macro level or a meso level close to macro.

The Analysis of the Development of Gluten-Free Bread

This task involves the development of gluten-free food products for people that cannot digest gluten. Corn that does not contain gluten may be used as an alternative. However, gluten is a necessary component if dough is to rise, resulting in the desired texture of bread. For an address to the task, it is necessary to know more about the function of gluten. To capture the released gases (CO_2) during fermentation, the dough needs to be elastic though strong enough. The strength of the walls of the 'pores' that capture the gases is highly influenced by gluten. Gluten contains of a network of long intertwined chains absorbing water and capturing gases. Such a hydrophilic network structure can explain the strength and elasticity of the walls. Hydrocolloids have the ability to form such structures. The process of 'preparation of dough' and 'fermentation' mainly determines the final properties of the bread. The structures in the dough are fixed during baking.

Exemplary statements of the expert are:

- During mixing of dough larger aggregates arise from gluten (meso-structures)
- If gluten is too loosely distributed in the matrix, then the dough will collapse (structure–property relation)
- If the distribution is loose then the bread rises badly (structure–property relation).

In the documents, six different meso-levels are found. For example, dough contains gas cells (10^{-4} m), enclosed by walls made up of a matrix with embedded starch granules (10^{-5}m). Granules, degraded due to enzyme attack (10^{-6} m), are held together by gluten fibres made up of gluten particles (10^{-7} m). These particles form the long (protein) molecular chains (10^{-8} m), made up of a single unit (amino acids; 10^{-9} m). The elastic property of dough can be caused by the existence of a gluten network [structure] which is impermeable for gasses [property]. This gluten network is elastic [property] because chains of gluten particles [structure] can move with respect to each other.

The Analysis of the Design of a Flexible Bullet-Proof Vest

The task in this study focused on enhancing the flexibility and reducing the weight of a bullet proof vest (e.g. wearing it as a vest under tuxedos or evening dresses). Document analysis and expert consultation revealed that a number of specific structures at different levels are used. The vest is a combination of mats that are glued together with epoxy resin (Fig. 9.4). Each mat forms a densely woven pattern of strong polymeric fibres. The flexibility of the vest (property) can be enlarged in different ways. The expert was weighing alternative strategies, iterating between options, zooming in and out, checking consequences like: flexibility must not lead to divergence of fibres, because then the vest does not absorb enough energy and even the bullet will go through the vest. The balancing between flexibility and tightly woven fibres, leads to a new focus on the importance of the strength of separate fibres. The property 'strength' of the thread is related to the structure of the crystalline parts of the polymer: a shish-kebab structure[1] is strongly related to the strength of single fibres. Molecular ladder structures of polymer chains in the Kevlar fibres with regular patters of hydrogen bonds may result in a regular crystalline ordering. This will result in a higher strength of separate fibres.

The expert did not reason in a straightforward way from macro to micro, but alternated between different alternative solutions (mats glued together, a single mat, threads, fibres, other materials) and alternative reasoning for finding solutions by considering new relations between properties and structures.

Generalisation of the Outcomes on the Three Tasks

Three analogous but theme-specific conceptual schemas have been constructed, with systems which have several nested sub-systems (Meijer et al., 2005). Relevant microstructures at different meso-levels can be assigned to appropriate scales. In such conceptual schemas, 'structure' can be defined as the distribution over space of the components in a system. Physical building blocks of such a system are regions that are bounded by a closed surface (Walstra, 2003), where at least some of the properties within such regions are different from those in the rest of the system.

Intermediate meso-structures (and models of these structures) were necessary when addressing the specific theme-related task. Properties could be assigned to meso-levels as well, although properties usually are closer to the macro-level. There appeared to be no fixed number of meso-levels, and experts did not order their reasoning in a fixed manner of macro $\rightarrow$ $(\text{meso})_n$ $\rightarrow$ micro or micro $\rightarrow$ $(\text{meso})_n$ $\rightarrow$ macro; their reasoning is characterised by reorientation and iteration. Most structure–property relations bridge a gap of three or four orders of magnitude of ten, when descending from macroscopic phenomena to meso-structures, and they mostly do not directly relate to the macro- and micro-level. Such relations between the highest and lowest level are very rare: In total, three out of the 22 identified structure–property relations were identified in the experts' protocols. Usually textbooks, research journals and other relevant papers do not present a system of nested structures. The separate representations could be found, however, mostly presented

---

[1] Heterogeneous nucleation of polymer crystallization resembling a visualized metaphor: compare the way meat is prepared in an oriental way: shish – kebab.

in a non-systematic way and without a clear reference to sizes and scales. These documents did not systematically reveal different visualisations of (meso- and micro-) structures within a nested scaled system, and structure–property relations were seldom explicitly mentioned.

Structure–property relations usually have a qualitative character (words, causal relations) and can be expressed as if–then clauses by ‘*if* this is an existing property, *then* it is caused by this type of structure’ or ‘*if* this is the existing structure, *then* probably this property can be expected’. Structure–property relations at the same scale (horizontally) were not found: all relations were links between two different (meso-) levels. Structure–property relations are different for the different tasks, and even within the same domain (e.g. ceramics) may well be different when the type of requirements is different (e.g. unbreakable versus resistant to certain chemicals). The relations will be specific for specific structures and specific properties, e.g. the strength of a jacket, a set of mats, one mat, a cluster of fibres, or one fibre.

To summarise: in authentic tasks, we have established that structure–property relations can be described by a dynamic system of structures, properties and their interrelations. Within the limits of our study we have derived a generalised conceptual schema, which we expect to be useful to teach macro–micro problems in which structure–property relations can be explicitly used (Figs. 9.2, 9.3 and 9.4). The system of nested structures, systematically assigned to appropriate scales, and the properties of the different structural components reveal a conceptual schema necessary for macro–micro thinking. The system of relevant nested structures and the explicit relations between structures and properties form the backbone of macro–micro reasoning. Depending on the task, a number of different meso-levels are relevant and

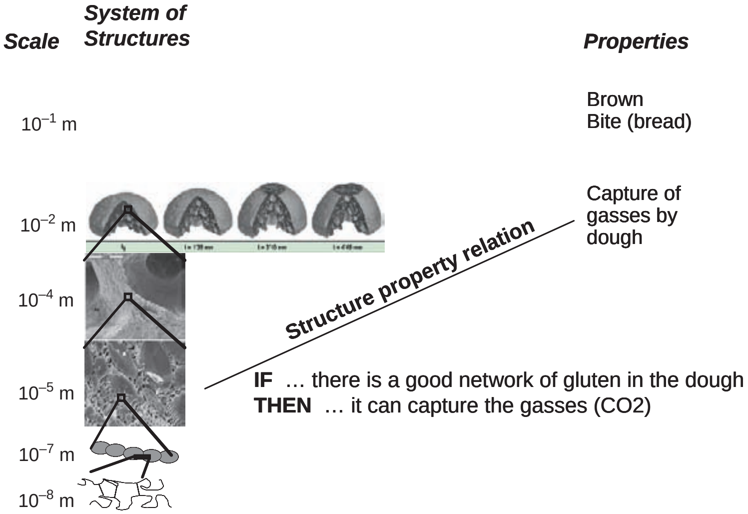


Fig. 9.3 The conceptual schema of micro–macro thinking for the task designing gluten-free corn bread, with the explicit use of structure–property relations

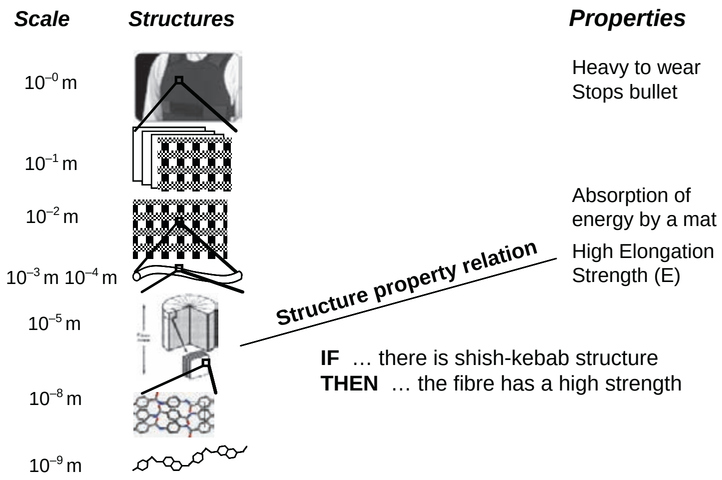


Fig. 9.4 Conceptual schema of the design of a bullet-proof jacket derived from the experts' consultation. An example of a structure–property relation is marked as a *line*

a certain set of explicit structure–property relations are necessary until sufficient structures, properties and their interrelations are available in the system to solve the tasks. Structuring of atoms and or ions at the micro level in a certain pattern should only be used when this is necessary to complete the task.

The conceptual schemas (Figs. 9.2, 9.3 and 9.4) represent macro to micro thinking in a systematic way (*Sub*). These have resulted from relevant socio-scientific tasks of social practices related to the chemical and technological domains (*Phil*). These conceptual schemas form the core of the substantive curriculum for macro–micro thinking; the authentic tasks from which these schemas originate define the type of community of practice in which the students' learning takes place (*Ped*). Both the authentic task as context and the bridging of the large step from macro to micro by several smaller steps should make the teaching and learning process meaningful for students. The learning process can start at a concrete, phenomenological (macro) level. At this level, phenomena or properties are observed and can be explained with intuitive notions of students. By introducing appropriate scientific concepts and relations, a more scientific explanation can be given for the observed phenomena or properties. Structures can be introduced by using visualisation of the structures at the macro level and the larger-scale meso-levels, and modelling of the 'invisible' structures to derive the necessary structure–property relations and experiments, using analogies (Treagust, Harrison, & Venville, 1998).

Towards Coherency with the Pedagogical Substructure of the Curriculum

The new conceptual schemas derived in the first part of this chapter could thus be used to design context-based units by a design research approach (Van den Akker, Gravemeijer, McKenney, & Nieveen, 2006; Bulte et al., 2006). Two of the three tasks could be used to design such units, because related student experiments in this field could be developed within the limits of the school laboratory: one unit about development of gluten-free bread and a second unit about the design of unbreakable crockery (Meijer, 2007; Pavlin, 2007). In a small-scale enactment of (parts) of the units, 8–14 students (age 17, pre-university level) were involved. Classroom observations, students' materials, video and audio-taped discussions, interviews, and pre- and post-questionnaires were used as data sources. The outcomes were compared to the expected outcomes. With these data, the actual learning process was compared with the learning process that was expected in the theory-based design of the units.

The Design of a First Unit

The first unit, about the development of gluten-free corn bread (cf. Fig. 9.3), is to facilitate the learning of macro–micro thinking using structure – property relations in a meaningful teaching and learning sequence. For this, we have maintained the coherency between the defined (authentic) task (*Ped*) and the newly derived substantive content (*Sub)*. It is essential to create with students a community of practice that closely resembles the authentic (community of) practice the authentic task originates from.

The participation within a community (*Ped*) was planned as follows. After a short introduction to the problem, the students have to use their common sense knowledge to address this task. Students become involved in the task to develop gluten-free bread. It is anticipated that students became motivated by the socio-scientific issue that an increasing part of the population has become intolerant to gluten in their food. In this way, the students were expected to be willing to form a community in which they design (and thus analyse) a gluten-free bread with their teacher as a senior member and project leader of the practice. Different teams of students of this community subdivided the different tasks under supervision of their teacher (as a project leader). Several plenary sessions were planned to coordinate the work. Subsequently, the students should discover that they need more knowledge about the structure of dough prepared from corn to modify the ill-developed properties of corn-bread. Since the community resembles the authentic community of practice, this content could be expected to come to the fore, and should provide the relevant concepts for addressing the task. The students had to look more precisely into the function and the structure of the gluten, apparently necessary to bake high-quality bread. Their investigations were directed towards the selection of a replacement for the gluten. The texts they had to study were translated and modified versions of authentic research articles. It was expected that students wanted to know more about the molecular structure of gluten, to come with a well-informed selection of some hydrocolloids that can replace gluten when baking bread based on corn dough. The students were not a priori provided with the conceptual schema for the development of gluten-free bread (cf. Fig. 9.2). The pedagogical approach was that they had to gradually (re)construct such a schema during their design task, and that the complete schema was discussed in a reflection activity at the final phase of the teaching and learning process.

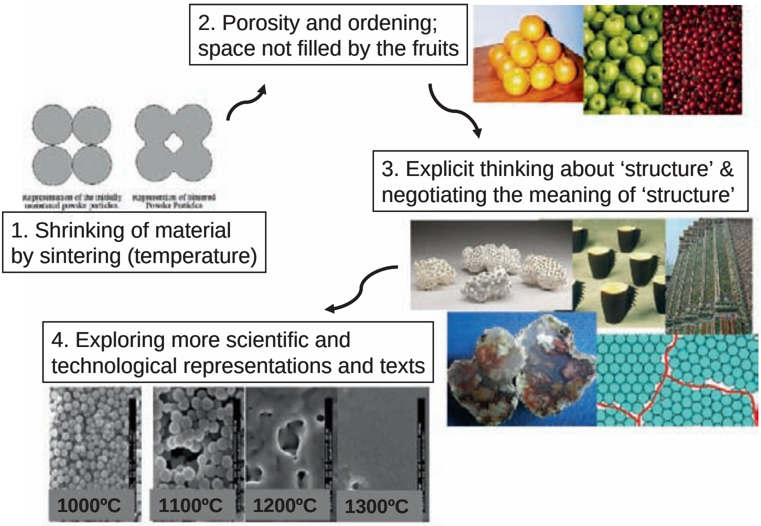
Evaluation of Implementation in the Classroom

Most of the expected learning and teaching activities proceeded as expected. As a result of the motivating task, students became involved in the planned social practice. The students identified that a well-developed dough is essential for baking bread with the desired texture. They related the rising of bread to the capability of a matrix of the dough to capture the CO_2 gasses. This can be achieved by absorption of water by the dough which leads to a flexible and strong matrix. The students could relate this to properties of the walls: these should capture gasses. Such a dough-matrix should not collapse. Some activities, however, delineated from the expected outcomes, and led to new questions about the pedagogy of the teaching and learning process. This particularly involved the concept of 'structure' at meso-levels below the scale of 10^{-5} m. When more abstract representations of structures were necessary for reasoning, the meaningful development of the system of structures came to a hold, and no further development of the structure–property relations took place.

Adjusting the Pedagogical Substructure of a Unit

An explanation for these findings can be found in the implicit use of and therefore poor development of the concept 'structure'. As long as 'structures' are related to visible and imaginable level, intuitive reasoning could take place. However, further concept development involving more abstract models needed attention. To start with that, we decided that we had to be more precise about the notion of 'concept'. As a starting point, we defined concepts as abstractions, representations of reality in our minds, not the realities themselves. We define concepts as *perceived regularities in events or objects, or records of events or objects designated by a label* (usually a word; Novak, 2002). The meaning of these perceived regularities is situated (Van Oers, 1998) and determined by their belief system of existing knowledge and notions (Vygotsky, 1986; Klaassen & Lijnse, 1996). This belief system should be viewed as 'explanatory frameworks' rather than fully specified theories (Nakhleh et al., 2005).

The main implication for designing a second unit involved the evoking of students' existing belief system of the concepts 'structure' and 'properties' by means of photographs of recognisable 'structures' (see for example the photographs of the packing of the fruit in Fig. 9.5). This step is essential for finding a common ground that forms a basis for understanding between the teacher and the students (Klaassen & Lijnse, 1996). For investigating this aspect of the pedagogical structure, we designed a second unit. The unit about unbreakable ceramics involved a less complicated task compared to the development of gluten-free bread, and ensured



1 *Assignment:* Try to describe the sintering process. Make a drawing of the step which has the largest influence on the strength.

Assignment: Can you relate the sintering process to the strength of the ceramics?

2 We can describe the system of fruit with the amount (percentage)of the space which is not filled with material. There are pores, canals and holes between the fruits. This is called porosity.

Assignment: Can you arrange the pictures from chaos to structured? Explain your order of the pictures.

Assignment: Can you find some similarities and differences between the fruit and clay particles?

3 Look at the different pictures.

Assignment: Can you describe what the structures are for each of the photographs?

Assignment: Can you describe what the properties are for each photograph?

Assignment: Define collectively what you consider as 'structure'and as 'property'

4 *Assignment:* What happens when the material is heated from 1000ºC up to 1300°C? Write down in your own words.

Fig. 9.5 Sequence of activities to develop the conceptualisation of porosity and structure in the unit about unbreakable crockery (Example of expanding the meaning of the concepts by activities that are meaningful for students at every step of the teaching and learning process)

that evaluation outcomes were not too much situated and connected to one of the tasks. Similarly, as for the unit about gluten-free bread, we also maintained the coherency of the activity and its contents derived from the related authentic task (see text above and Fig. 9.2).

With the following example, we illustrate how in a sequence of activities the students' intuitive notions about the influence of particle size and the sintering temperature of the clay on the properties of ceramic materials have productively been used (Klaassen & Lijnse, 1996; Mortimer & Scott, 2003; Duit & Treagust, 2003;

Vygotsky, 1986; Fig. 9.5, assignment 1). More precisely the sequence of teaching and learning activities needed to start at what we describe as a concrete level (Davydov, 1975; Roth & Hwang, 2006). Before studying scientific and technological representations and texts about the influence of the sintering temperature on porosity, the photographs of the fruits were to be used to develop the conceptualisation of porosity and structure (assignment 2 in Fig. 9.5). Next, representations of recognizable photographs of different ‘structures’ are presented, and based on these photographs the meaning of the concept of ‘structure’ and also ‘property’ is to be negotiated with students (assignment 3 in Fig. 9.5). After collectively defining the concepts of structure and properties, these concepts can be expanded with representations like symbols, figures, words and relations to properties, much more in agreement with the scientific meaning of the concept of structure in this domain (assignment 4, Fig. 9.5).

This sequence of activities (Fig. 9.5) is justified from the perspective of learning (*Ped*) as follows. The activities in which the students expand the meaning of the concepts should be meaningful for them at every step. Students use their existing knowledge (including intuition), senses, sources of information and social aspects like values and norms when constructing new associations and relations to concepts. These relations and associations which influence their decisions about truth and meaningfulness (Vygotsky, 1986) are important because they are decisive whether the expansion of the knowledge is indeed accepted for further use or not (Bartsch, 1998). These considerations originating from rethinking our empirical findings are an extension of the pedagogical substructure (*Ped*).

Implementation and Evaluation of the Second Unit

It appeared possible to make intuitive notions about the concepts of ‘structure’ and ‘property’ productive for classifying structure–property relations in structures and properties. The intuitive notions for structure were: ‘*an ordering, arrangement*’, ‘*how things are connected with each other*’, ‘*how things are build*’. And for property the intuitive notion was: ‘*what something can or does*’, ‘*a function*’. These notions appeared to be sufficient for these students to understand the information in the (authentic scientific) documentation. In the next activities, this way of defining these key concepts was good enough for the students to arrange the new scientific and technological terms in structure, property or process variable during sintering of the ceramic materials as were planned in the unit. Using this arrangement, the meanings of the concepts ‘structure’ and ‘property’ are expanded to respectively, ‘*a construction*’, ‘*an ordering*‘, ‘*a pattern*’ and ‘*a characteristic of a material*’. Subsequently, the group of students collaboratively ascertained these meanings, and constructed a conceptual schema for this authentic task (cf. Fig. 9.3) in a reflection activity in the final phase of the teaching and learning process. This learning activity within the adapted version of the authentic practice (*Phil* & *Ped*) consequently led to the students’ own construction of the relevant content within this unit (*Sub* & *Ped*).

In Retrospect

On reflection, we proposed to use the analysis of authentic socio-scientific tasks as a route to formulate a new coherent vision on the domain of macro–micro reasoning in the chemistry curriculum. The proposed conceptual schema of macro–micro thinking can significantly address the problems in the learning of micro–macro thinking of students at secondary school for tasks in biochemistry and inorganic chemistry (Millar, 1990; De Vos & Verdonk, 1996; Harrison & Treagust, 2002). We think that the explicit use of structure–property relations as arguments may enhance the public understanding of science and technology. The use of meso-structures between the macro- and micro-level and structure–property relations as a tool to iterate between macro- and micro-level is essential to connect student learning of these chemical concepts to the contexts of their everyday lives and to contemporary science and technological issues. The presented conceptual analysis and its exploration with students have promising features to include contemporary science issues in the chemistry (science) curriculum, such as genomics and new innovative micro- and nano-structured materials.

To connect these outcomes to Van Berkel's analysis of the problematic nature of micro–macro thinking in chemistry, we have developed an alternative as a way to escape (Van Berkel, 2005). Using Van Berkel's framework, firstly, we understand what situation we had to escape from: the rigid combination of predominant substructures of main-stream chemistry curricula. Secondly, we expect to have found a route to escape by redefining a philosophy of chemistry based on social practices that at the same time determines the pedagogical and substantive substructure of learning to think in terms of *macro–micro thinking* using explicit structure–property relations. These levels include meso-levels with a scale ranging from metres to centimetres to millimetres to a nanometre level.

References

Aguilera, J. M. (2006). Food product engineering: building the right structures. *Journal of Science of Food and Agriculture*, *86*, 1147–1155.

Anderson, J. R., Greeno, J. G., Reder, L. M., & Simon, H. A. (2000). Perspectives on learning, thinking, and activity. *Educational Researcher, 29*, 11–13.

Bartsch, R. (1998). *Dynamic Conceptual Semantics*. CSLI Publications & FOLLI.

Besson, U., & Viennot, L. (2004). Using models at the mesoscopic scale in teaching physics: two experimental interventions in solid friction and fluid statics. *International Journal of Science Education*, *26*(9), 1083–1110.

Bulte, A. M. W., Westbroek, H. B., de Jong, O., & Pilot, A. (2006). A research approach to designing chemistry education using authentic practices as contexts. *International Journal of Science Education*, *28*(9), 1063–1086.

Cussler, E. L., & Moggridge, G. D. (2001), *Chemical product design*. Cambridge: Cambridge University Press.

Davydov, V. V. (1988). The concept of theoretical generalization and problems of educational psychology. *Studies in East European Thought, 36*(3), 169–202.

De Vos, W., & Verdonk, A.H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching, 33*(6), 657–664.

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning.*International Journal of Science Education, 25*(6), 671–688.

Gilbert, J. K. (2006) On the nature of ‘context’ in chemical education. *International Journal of Science Education, 28*(9), 957–976.

Han, J., & Roth, W.-M. (2006). Chemical inscriptions in Korean textbooks: Semiotics of macro- and micro-world, *Science Education, 90*, 173–201.

Harrison, A.G., & Treagust, D.F. (2002). The particulate nature of matter: Challenges in understanding the microscopic world. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 189–212). Dordrecht: Kluwer Academic Press.

Jacobs, S. (2000). Michale Polanyi on the education and knowledge of scientists. *Science and Education, 9*, 309–320.

Justi, R., & Gilbert, J.K. (2002). Models and modelling in chemical education. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 47–68). Dordrecht: Kluwer Academic Press.

Kelly, G. J. (2007). Discourse in science classrooms. In S.K. Abell & N. G. Ledermann (Eds.), *Handbook of research on science education* (pp. 443–469). Mahwah, NJ: Lawrence Erlbaum Associates.

Klaassen, C. W. J. M., & Lijnse, P. L. (1996). Interpreting students’ and teachers’ discourse in science classes: An underestimated problem? *Journal of Research in Science Teaching, 33*, 115–134.

Lijnse, P. L., & Klaassen, C. W. J. M. (2004). Didactical structures as an outcome of research on teaching learning sequences? *International Journal of Science Education, 26*(5), 536–554.

Meijer, M. (2007). *Ontwerp en Evaluatie, 1e ronde chemie van een klevend network [Design and Evaluation of 1st unit ‘Chemistry of sticky network’].* Utrecht: Utrecht University, Freudenthal Institute for Science and Mathematical Education. Document Doc07-01. Available online: http://www.cdbeta.uu.nl/onderzoek/publicaties.php [cited 03-10-2007].

Meijer, M. R., Bulte, A. M. W., & Pilot, A. (2005). *A Conceptual Analysis of micro-macro thinking – Using structure-property relations in chemical education.* Paper presented at the ESERA conference, Barcelona.

Millar, R. (1990). Making sense: what use are particle ideas to children? In P.L. Lijnse, P. Licht, W. de Vos, A. J. Waarlo, *Relating macroscopic phenomena to microscopic particles* (pp. 283–293). Utrecht: Utrecht University, Freudenthal Institute for Science and Mathematical Education, CDβ press.

Mortimer, E., & Scott, P. (2003). *Meaning making in secondary science classrooms*. Buckingham, UK: Open University Press.

Nakhleh, M.B., Samarapungavan, A. & Saglam, Y. (2005). Middle school students’ belief about matter. *Journal of Research in Science Teaching, 42*(5), 581–612.

Novak, J. D. (2002). Meaningful learning: The essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of learners. *Science Education, 86*, 548–571.

Pavlin, J. (2007). *Using students’ intuitive notions about ‘structure’, ‘property’ and ‘structure-property relations’ for the learning of macro-micro thinking.* Ljubljana: Univerza v Ljubljani, Pedagoška fakulteta, Fakulteta za kemijo in kemijsko Tehnologijo & Utrecht: Freudenthal Institute for Science and Mathematics Education (Unpublished Master thesis). Document Doc07-02. Available online: http://www.cdbeta.uu.nl/onderzoek/publicaties.php [cited 03-10-2007].

Pilot, A., & Bulte, A. M. W. (2006). The use of “contexts” as a challenge for the chemistry curriculum: Its successes & the need for further development and understanding. *International Journal of Science Education, 28*(9), 1087–1112.

Polanyi, M. (1958). *Personal knowledge*. London: Routledge & Kegan Paul.

Prins, G. T., Bulte, A. M. W., Van Driel, J. H., & Pilot, A. (2008). Selection of authentic modelling practices as contexts for chemistry education. *Accepted for publication in International Journal of Science Education, 30*(14), 1867–1890.

Rivet, A., Slinger, J., Schneider, R., Krajick, J., & Marx, R. (2000). *The evolution of water.* Paper presented at the Annual Conference of the National Association for Research in Science Teaching, New Orleans, LA.

Roth, W. M. (2006). Does mathematical learning occur in going from concrete to abstract or in going from abstract to concrete? *Journal of Mathematical Behaviour, 25*, 334–344.

Treagust, D. F., Harrison, A. G., & Venville, G. J. (1998). Teaching science effectively with analogies: an approach for pre service and in service teacher education, *Journal of Science Teacher Education, 9*(2), 85–101.

Van Berkel, B. (2005). *The structure of current school chemistry – a quest for conditions for escape.* Utrecht: University of Utrecht.

Van Berkel, B., Pilot, A., & Bulte, A. M. W. (in press). Micro–macro thinking in chemistry education: Why and how to escape. In J.K Gilbert & D. Treagust (Eds.), *Multiple representations in chemical eduction*. Springer

Van den Akker J., Gravemeijer, K., McKenney, S., & Nieveen, N. (Eds). (2006). *Educational design research.* London: Routledge.

Van Oers, B. (1998). From context to contextualization. *Learning and Instruction, 8*, 473–488.

Vygotsky, L. (1986). *Thought and language*. Cambridge, MA, MIT Press.

Walstra, P. (2003). *Physical chemistry of food*. New York: Marcel Dekker Inc.

Wenger, E. (1998). *Communities of practice, learning, meaning, and identity*, Cambridge: Cambridge University Press.

Chapter 10
Historical Material in Macro–Micro Thinking: Conceptual Change in Chemistry Education and the History of Chemistry

Lars Scheffel, Wiebke Brockmeier and Ilka Parchmann

Abstract In addition to teaching about science and the nature of science, historical approaches in chemistry education can be used to promote conceptual change concerning micro–macro relationships. Furthermore, historical approaches provide a pool of ideas for learning contexts and for storytelling. In this chapter, we present an overview about the historical development of micro–macro thinking. Parallels to students' conceptions are pointed out to give hints for the design of teaching material. Results of teaching experiments are presented, using historical approaches to initiate the students' discussions and reflections about their own concepts.

Introduction

Micro–macro thinking may be *the* important approach for scientists to explain and to manipulate the world. However, for students and novices, micro–macro thinking may be one of the major difficulties in the process of learning the sciences (Ben-Zvi, Silberstein, & Mamlok, 1990; Lijnse & Licht, 1990). What does micro–macro thinking in chemistry mean? Three main aspects have to be considered: atomicity, chemical bonding and structure–property relations. *Atomicity* means that students have to be aware of the particulate nature of matter, to be able to discriminate between different particle models and to distinguish between properties of matter and atoms, molecules or ionic structures. *Chemical bonding* requires knowledge about different models, such as covalent, ionic and metallic bonding, besides the different types of intermolecular force. The aspect of *structure–property relations* builds a bridge between the macroscopic and microscopic representation of matter. In all three aspects, many misconceptions and learning impediments are known. Important steps in the history of science can be identified which reflect some of the students' conceptions in a certain way.

L. Scheffel (✉)
University of Oldenburg, Oldenburg, Germany
e-mail: Lars.scheffel@uni-oldenburg.de

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_11,

However, school education in practice has rarely taken such knowledge into consideration. One reason may be teachers' incomplete knowledge of not only their students' ideas but also about pathways and contexts of conceptual developments, both within students and in the history of science. Another reason could be the lack of good teaching and learning materials to bring these two perspectives together. In this chapter, we discuss parallels and differences between historic development and students' ideas about micro–macro thinking and offer some ideas of how the use of historic elements can become fruitful for informing teaching and learning processes.

Theoretical Considerations: The Value of the History of Chemistry

Parallels between historic developments and the conceptual developments of learners have often been postulated theoretically (Piaget & Garcia, 1983, but for a contradiction of this view see also Gault, 1991) and described for different concepts (e.g. van Driel, De Vos, & Verloop, 1998 including that of chemical equilibrium; Mas et al. (1987) for ideas about gases; Pfundt (1975) for ideas about the smallest particles of matter and many others). Theoretical analyses and empirical investigations of aspects of the history and the nature of science have also been discussed from different points of view (e.g. Gault, 1991; Driver et al., 2000). For science education in general, Wandersee and Griffard (2003) discuss four main purposes for the use of historic elements in teaching and learning:

1. Students can learn about the nature of science as a social construction and activity,
2. Students' critical thinking can be trained,
3. Historical knowledge can help teachers to embed chemical topics in their curricular and social context, and
4. Parallels between students' conceptions and historical ideas in science can be shown.

Other authors have additionally argued that, by the use of historic elements:

5 Rich and various learning opportunities can be constructed from daily-life experience, historical and scientific problems,
6 Students can be motivated by the telling of historical stories (Herron, 1975; Kubli, 2005; McKinney & Michalovic, 2004),
7 Students can identify themselves with historical researchers (Matuschek & Jansen, 1985; Janes, 2004),
8 Students learn about chemistry as being a part of intellectual history and its position in culture (Matuschek & Jansen, 1985) and
9 By dealing with historical controversies, students' preconceptions can be affected (Jansen et al., 1995).

Accepting these arguments, it should be a matter of course for teachers to use historic elements in teaching science in general and chemistry in particular. However, the application may not be as simple as it appears. The use of historic elements will only become fruitful if the arguments made by Wandersee and Griffard are indeed taken into consideration. Telling the students stories about well-known researchers will present them as people but does not provide students with the background of the developmental process of a certain idea in a certain period of time. Showing the students original material like letters and experiments may offer ideas of explanation – but the material on its own does not deliver the theoretical background of a certain time and it does often not give any information about the general interests and conditions that researchers followed in a certain period of time. We can therefore ask critically: why should students in a completely different context with completely different interests develop similar ideas like those of researchers in the past? However, we often find such analogies between the two and the following paragraphs will offer some reasons for such parallel developments.

The idea of correlations between individual cognitive development and the process of historical conceptual development is rather old. Matthews (1992) localises the first mentioning of this idea in Hegel's *The Phenomenology of Mind*. Later, in the end of the nineteenth century, this thought had been picked up by Mach and Duhem in their thoughts about the nature of physical laws. With Piaget's *Genetic Epistemology* (1970), this idea experienced a powerful renaissance with growing influence on science education. According to Piaget,

> the fundamental hypothesis of genetic epistemology is that there is a parallelism between the progress made in the logical and rational organisation of knowledge and the corresponding formative psychological process (p. 13).

In the late 1980s, the influence grew again. First, Kuhn (1967) postulated the idea of 'scientific revolutions'. Later, in the light of research in conceptual change, parallels between the history of science and in psychological ontogeny were drawn, especially by Posner et al. (1982). An overview related to Kuhn's impact of science education can be found in Matthews (2004). To illustrate this idea, we will give short insights into both the theory of conceptual change and into paradigm change in the history of science. Kuhn's ideas will be explained rather extensively in order to get a firm basis for comparison between philogeny and ontogeny.

According to Kuhn's theory of scientific revolutions, science proceeds in cycles of 'normal' science, crisis, paradigm change, followed by a phase of reconsolidation. 'Normal' research means to find problems based on shared scientific principles, building hypothesis and solving these problems based on the existing paradigm. Paradigms are

> scientific achievements, that some particular scientific community acknowledges for a time as supplying for its further practice (Kuhn 1976).

These paradigms guide the work of scientists. Furthermore, they serve as a predicting device for the behaviour of nature (in this case chemistry) in hitherto unexplored fields. During this 'normal' research, anomalies can be observed, which contradict the predicted behaviour and violate the tenets of the existing paradigm. Paradigm change occurs when the number of contradicting observations reaches a critical mass, such that the old paradigm can not longer be defended against the contradictions. Certainly, *one* violation of the paradigm is not sufficient to initiate paradigm change. Paradigms, as analysed by Kuhn, are defended by scientists with several techniques. One technique is to ignore the anomaly, for example, by not publishing it. Another technique is the slight modification of ‘outer regions’ of the paradigm. For example, some parameters or features of a certain scientific theory can be changed without touching the ‘hard core’ of the theory.

How does a scientific revolution take place? If the number and seriousness of violations to the paradigm accumulates, science slips into a crisis. In most cases, researchers will not renounce the paradigm, but develop numerous ad-hoc modifications of their theories. A crisis can end in three ways. (1) Researchers find a way to handle the anomalies with the tools of the existing paradigm, (2) the problem resists solution and is set aside for future generations or (3) proposals for a new paradigm are discussed within the scientific community. To judge between two paradigms, it is not sufficient to compare the new paradigm with nature in order to explore its explaining and predictive power. It must also be compared with the ‘old’ paradigm. Paradigm change is, according to Kuhn, not a cumulative process: It is revolutionary in the sense of a complete reconstruction of a scientific field from new fundamentals (Kuhn, 1976).

These historical implications lead straight back to the theories of conceptual change. Especially the well-known theory by Posner et al. (1982) is much inspired by epistemological considerations. Posner et al. themselves characterise their theory of conceptual change as

> based on a cognitive psychology and a Kuhnian (or, more precisely) Lakatosian epistemology (p. 106).

As a second source, Piaget’s theory of accommodation has to be mentioned, which greatly influenced the meaning of the term ‘conceptual change’. How does conceptual change take place? And what are the similarities to the Kuhnian epistemology? We will again quote from the Posner et al. (1982) paper (see also Table 10.1):

Table 10.1 Similarities between paradigm change in the history of science and in conceptual change

Paradigm change (Kuhn)	Conceptual change (Posner et al.)
Phase of ‘normal’ science: Fruitful application of paradigms.	Fruitful application of preconception
Crisis: Accumulations of facts contradicting the paradigms	Learner becomes dissatisfied with his conception, cognitive conflict results
Debate about new models, new paradigms become accepted	Acquiring of the new conception, if it is logical, plausible and fruitful
New phase of ‘normal science’	Replacement of the old conception, coexistence of multiple conceptions or restructuring of existing conceptions.

> 1. *There must be dissatisfaction with the existing conceptions*. Scientists and students are unlikely to make major changes in their concepts until they believe that less radical changes will not work. Thus, before an accommodation can occur it is reasonable to suppose that individuals must have collected a store of unsolved puzzles or anomalies and lost faith in the ability of their current concepts to solve these problems.

> 2. *A new conception must be intelligible*. Individuals must be able to grasp how experience can be structured by a new concept sufficiently to explore the possibilities inherent in it. [. . .]
> 3. *A new conception must appear plausible*. Any new concept adopted must at least appear to have the capacity to solve the problems generated by its predecessors. Otherwise it will not appear a plausible choice. [. . .]
> 4. *The new concept should suggest the possibility of a fruitful research program*. It should have the potential to be exceeded, to open up new areas of inquiry (p. 214).

What are the *objections* to these ideas? The equivalence between students' ideas and scientific conceptions had often been doubted. The main argument of many authors has been that both sides are incommensurable. Students' conceptions with limited empirical foundation, often ad hoc formulated or post hoc reconstructed by researchers, have a completely different ontological status to empirically based ideas that are carefully formulated and sharpened by debate among scientific peers. Gault (1991) sketches some crucial differences as follows:

> 1. Some historical data, meaningful in the experience of early scientists, might not be meaningful or accessible to modern students. For example, observational data about planetary motion (or even the nature of planetary motion itself) is not something which easily connects with the everyday experience of students today.
> 2. Some of the arguments that were compelling for particular scientists may not be compelling for particular students today. It is probably true, for example, that many of the arguments which moved scientists on from the "impetus" view [the ancient theory on moving bodies] would not be suitable for students because they are too technical.
> 3. Most students do not possess the same motivation to work to develop their understanding that early scientists had. The painstaking and tenacious search through alternative points of view which led Darwin to the publication of his "The Origin of Species" may not be a characteristic of many students of any period (p. 138).

What are the conclusions, can we draw from these – rather obscure – fields for our consideration of micro–macro thinking? Points are that

1. In a constructivist view of teaching and learning, students' beliefs (conceptions, previous ideas) do resemble scientific conceptions or paradigms epistemologically. The observed similarities (not identities!) could be used to enhance conceptual change in classroom teaching.
2. There are vague parallels between the processes in knowledge development in science education and in the history of science, although the mental processes involved are quite unknown.
3. Some semblances can also be found in the content of ideas: Similarities between students' conceptions and historical ideas have been described in many fields of science. These relations can be useful in science teaching, but a closer examination in each specific situation is certainly necessary.
4. Students are students. Scientists are Scientists. History of science and science education are different things and cannot be correlated to each other without keeping in mind educational aims and methods as well as the different contexts and cultural background of school science and historical science. Still, historic ideas can be useful to initiate students' ideas too.

The Model of Educational Reconstruction

Despite this much-discussed theoretical background, the number of concrete studies comparing historical ideas and students' conceptions is fairly low in chemistry education. Furthermore, most studies cited deal with isolated topics. Systematic overviews concerning basic ideas like micro–macro thinking, chemical reaction, the particulate nature of matter, energy conversions etc. are mostly not available, except for van Driel et al. (1998) and the case of the chemical equilibrium.

The Model of Educational Reconstruction (Kattmann and Gropengießer, 1997) offers a structure in which 'microscopic processes' can be investigated in depth to explain 'macroscopic learning outcomes', and to use this knowledge to design and to evaluate more teaching and learning approaches in practice. The central approach of this model is the iterative investigation of historic and modern scientific explanations on the one hand and students' explanations on the other (Fig. 10.1). Within the Model of Educational Reconstruction, students' conceptions are seen as internally consistent and fruitfully applicable as scientific conceptions. Furthermore, due to the model's foundation in constructivism, their ontological and epistemological status is equivalent to that of scientific conceptions. Thus, the two become comparable. From the comparison of those two positions, a novel teaching structure can be developed. For this research three steps in an *iterative* process are necessary: (1) the hermeneutic investigation of scientific ideas, (2) the qualitative investigation of students' preconceptions and (3) the formulation of an educational structure. Here, the iterative investigation is a process of continuous movement back and forth between both perspectives, which derives deeper questions about the background conditions and contexts of the observed developmental processes.

The first step is the investigation of recent and historical explanations concerning the topic. Significant publications, letters etc. of scientists are analysed in order to find their basic assumptions, hidden epistemological persuasions and the limitations as well as the inconsistencies of theories. For this step, each scientific work is seen as the *individual* view of one (or maybe two) researcher(s) on the topic. The focus of interest is not (only) the conceptual explanation itself, but the context of the development (e.g. the framing theories of that time, the general interests of investigation, the key observations), the applications and constraints of a concept and the meaning of different terms and concepts in different contexts and times. For the overall

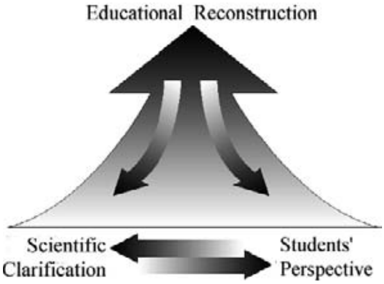


Fig. 10.1 The model of educational reconstruction (Kattmann and Gropengießer, 1997)

concept of micro–macro thinking, the first interesting question is the direction of investigation or explanation: Did an explanation start with a macroscopic observation which led to the development of a microscopic explanation, or was the microscopic idea already there and did this lead to a perception of a phenomenon and its interpretation? Another important question to ask is for the direction of ‘transfer processes’: In which cases were macroscopic properties transferred to microscopic models (e.g. Ben-Zvi et al., 1986) or even vice versa? Last but not least, the framing theories, both from daily-life and from a current scientific state of discussion, must be investigated. A well-known example for the influence of framing theories can be found in the history of chemistry, where the idea of a substance called ‘Phlogiston’ led to many misinterpretations of phenomena from our point of view that were completely coherent in the eighteenth century (Irwing, 1997; Marino & Kremer, 2002). Vosniadou (2007) and others have, in parallel, described the influence of framing theories for the development of students’ conceptual understanding, which leads to the second corner of the triangle.

The second step is the investigation of students’ conceptions. Here, the model focuses on the basic conceptions and not on isolated ideas concerning singular phenomena. The main questions here concern (1) the nature of basic conceptions, (2) the use of scientific language and terminology, (3) students’ ideas about science and (4) possible correspondences and/or differences between students’ ideas and scientific conceptions. One of the main ideas of the model is to confront students’ conceptions in a *positive* way. The crucial point is to consider their explanatory potential rather than their limitations.

For the third step, the formulation of educational guidelines, Kattmann and Gropengießer (1997) mention four main questions to be taken into account:

1. What are the most important aspects of the students’ conceptions, which have to be considered in class?
2. Which previous ideas have to be considered concerning the use of scientific terminology?
3. What are the possibilities of science teaching if students’ conceptions are taken into account?
4. Which daily life conceptions correspond to scientific ideas and how can they be used for appropriate and fruitful learning? (Kattmann and Gropengießer, 1997, p. 190).

The following pages present an insight into historic developments and students’ explanations of micro–macro thinking, taking into consideration as much background information as possible, and will describe some examples of teaching and learning situations derived from that knowledge.

Milestones in the History of Micro–Macro Thinking and Parallels to Students’ Ideas

Research into students’ conceptions has produced several outcomes. The literature reviews by Barker (2004), Driver et al. (2000), Garnett and Hackling (1995), Özmen (2004, especially for chemical bonding) and Coll und Treagust (2003, chemistry of metals) can help to develop a first overview. Numerous authors (e.g. Pfund, 1975; Schlöpke, 1991; Griffith and Preston, 1992; Mas et al., 1987) describe parallels between students' conceptions and historical scientific ideas. Schlöpke (1991), for example, points out similarities between students' conceptions concerning properties of matter and ideas in alchemist thinking. Lee, Eichinger, Anderson, Berkheimer, and Blakeslee (1993) mentions semblances between the ideas of Aristotle and students' conceptions about general aspects of the particulate nature of matter and the 'horror vacui'.

Of course, a mere mentioning of similarities does not help science education in any way. In the literature, students' difficulties in integrating daily-life preconceptions and scientific conceptions are widely documented. Similar problems occur also in science as the following example demonstrates. August-Ludwig Frankenheim (1801–1869) was a physicist in Breslau who was especially interested in the fundamental questions of matter. With countless series of measurements, he investigated the physical properties of crystals. Although he started his investigations with a continuous model of matter in mind, he came to the result that a discontinuous model would be more appropriate to explain the observed phenomena. Considering this cognitive conflict he wrote,

> I am really unwilling to enter the slippery area of these hypotheses and I am by no means convinced by the truth of this before mentioned proposition [the discontinuous model of matter]. A major part of scientists believes in its evidence, and they will, if they act consequently, come to the results which I have indicated. I deeply regret being unable to juxtapose this theory with another, based on a continuous model of matter, coming to results of the same importance. (Frankenheim, 1835, 311pp, translated by the authors).

In the next parts of this chapter, we explore similarities between students' conceptual change and paradigm change in the history of science and draw some initial conclusions about how to use these similarities in classrooms.

The Particulate Nature of Matter

Historical Development

Most school textbooks write about the 'invention' of atomism by Leukipp and Demokrit (450–360 BC, 460–371 BC). Both philosophers postulated that matter consists of discrete particles separated by empty space. They described these atoms as permanently moving, naming these particles 'atoms' from the Greek word for ('indivisible'). However, from our present day perspective, the Greek philosophers were talking about the particles that build up a substance, molecules, ionic lattices etc., not about single atoms. Still, it is interesting to see, which thoughts they had got purely by observing nature. One idea was that atoms must be separated by absolutely empty space, because otherwise, they would not be able to move. When two

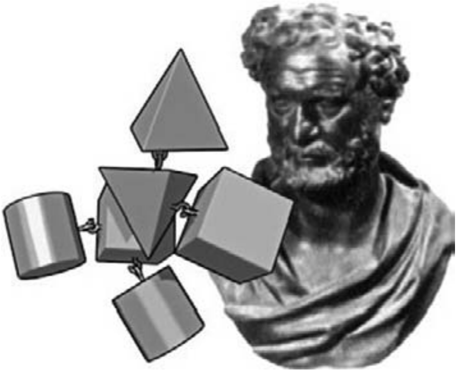


Fig. 10.2 Conception of atoms by Demokrit. (Picture taken from www.physicsmasterclaases.org)

particles collided, they should form a kind of chemical bonding by putting hooks into eyes (e.g. Geyer, 1995; Fig. 10.2).

Leukipp and Demokrit introduced two important principles: They explained differences in the specific weight of substances with different numbers of atoms in a definite space. Substances with a lower specific weight should contain fewer atoms per space unit than substances with a higher specific weight, so they were packed together more closely. Concerning the question of why some substances mix (for example wine and water) and others separate from each other (oil and water) they postulated a model of differently sized spaces between the particles. If two substances mix, their particles insert into the spaces between the particles of the other substance, whereas the reaction between two substances is characterised by a ‘bond’ between two or more particles. Leukipp und Demokrit emphasised the difference between a macroscopical and a microscopical view on matter. Even if a substance seems (macroscopically) to be totally homogeneous, it is microscopically inhomogeneous (Geyer, 1995; Stückelberger, 1979; Mansfeld, 1989). Their thoughts are particularly interesting as they have been purely philosophical. While in school education we often start with experiments, the ancient Greeks did not carry out any investigations, they simply observed nature and started thinking about how the world could be explained. Their interest was not a scientific interest; nevertheless they can be counted as the first scientists who developed a particle model for science.

Their theory can also be regarded as the beginning of micro–macro thinking in the written history of science: in a philosophical manner, macroscopic properties are projected, but not transferred on a pure hypothetical microscopic model (Weißbach, 1971).

Students’ Ideas in Comparison

In this section, we present some parallels to Aristotelian thinking. Aristotle strongly attacked the idea of atomism. For example, the idea of empty space between particles is not easy to grasp for students, as it was neglected by Aristotle. According to Novick (1978) and later on Novick und Nussbaum (1981), students think that atoms are only *one* compound of matter. Between atoms, there is ‘dust’, ‘nitrogen and oxygen’, ‘liquids’ or unknown gases. Other students said the atoms would be packed so closely, that there can be nothing else. If we follow Novick and Nussbaum (1981) argumentation, these ideas represent a ‘horror vacui’, the idea that nature always tries to avoid empty space. Aristotle (384–322 BC) also denied the idea of discrete particles of matter because he denied the idea of a vacuum between particles. To justify his theory, he relied on an experiment by the Greek philosopher Anaxagoras (500–428 BC) who took a crucible with black ink and added white colour in small droplets under constant stirring. He observed that the colour changed continuously from black to grey. Anaxagoras (and later Leukipp und Demokrit) concluded that there must be things in nature which are too small for our senses (Farrington, 1944). Aristotle, however, interpreted the experiment differently and denied the particulate nature of matter. He argued that the change of colour would have to proceed in steps if matter consisted of discrete particles.

In summary, for Leukipp and Demokrit, the empty space between the atoms was a key assumption in their model, because, if particles were closely packed, they could not move and substances could not be mixed. When asking students to philosophise about the nature of matter, we indeed find parallels to the ancient Greek thinking, both to the so-called ‘atomists’ and to the ‘continuous’ ideas of Aristotle and others. For example, Leukipp’s and Demokrit’s explanation for the specific weight of substances corresponds to one student conception: younger students especially tend to explain differences in the specific weight (but also hardness of substances) with differences in the closeness of particles (Fig. 10.6). They seldom take into account that the particles could have a different weight themselves.

This argumentation was strongly attacked by Aristotle who said that water can also move and flow without observable empty spaces in it. Maybe Aristotle simply overestimated the size of atoms as thought by Leukipp and Demokrit (Horne, 1975). To justify his denial of empty spaces between atoms, one student said: ‘Well, you can’t see open spaces in water’ (Lee et al., 1993, p. 257). Such misleading ideas about the size of atoms and particles are reported for students, too (e.g. Lee et al., 1993). Hence, learning difficulties can be explained by this frame: When expecting that particles should be observable but no such particles can be seen, why should a learner believe in the existence of atoms?

With regard to micro–macro thinking, another explanation could be that Aristotle could not follow the change in the level of representation from macro to micro level: his thinking remained on the macroscopical level. Using this example, the necessity of changing the representational level as well as the levels of explanation must also be discussed in the classroom. Although Aristotle’s ideas were much more elaborated than students’ conceptions, it could be fruitful to discuss in the classroom not only Leukipp’s and Demokrit’s ideas, but also Aristotle’s contradictions. This discussion may pick up some students’ cognitive conflict between their preconceptions and the models taught at school. Students would have the possibility of discussing some of their conceptions as a discussion about historical theories.

Structure–Property Relations

Historical Development

Scientists in the period of alchemy between the eighth and fourteenth century also developed some interesting theories concerning the particulate nature of matter. A common alchemistic theory was that matter is built up of substance without any properties (the ‘prima materia’). Properties, regarded as their own physical entities, could be added or removed (Schlöpke, 1991). Although alchemists often wrote about smallest particles, based on this scientific paradigm, the idea of ‘making gold’ did not seem as absurd as it seems for us today: properties could be added to substances, it would be possible to add the properties of gold to other metals. Using the Aristotelian idea that all substances were a mixture of the four elements water, air, soil and fire and their properties, it should also be possible to find the correct mixture for gold. The thinking of Paracelsus (1493–1511) concerning the properties of crystals shows this approach. According to Paracelsus’ theory, every crystal is made of three substances representing some of the properties of the whole crystal. *Sulphur* is responsible for combustibility, *mercury* for elasticity and low melting point and *salt* for hardness and the shape of crystals. With *sulphur, mercury* and *salt* Paracelsus did not think of real substances, they were ‘symbols’ for the properties of matter. According to Paracelsus, every substance has its own *salt, sulphur* and *mercury* (Hiller, 1952).

Students’ Ideas in Comparison

Parallels to historical ideas in students’ thinking have been pointed out by Schlöpke (1991) who analysed historical sources and compared the arguments with those in interviews with students. In order to explain chemical or physical phenomena, numerous students use explanations based on a ‘substantialisation’ of properties (Sanmarti, 1995). Those students think that properties can be seen as their own substance; a blue crystal, copper sulphate for example, consists of ‘crystal material’ and ‘blue colour’ (Schlöpke, 1991). Concerning micro–macro thinking, this students’ conception is quite problematic. The idea that properties were ‘own physical entities’ means that there were no relationships between microscopical and macroscopical properties. A typical example is the students’ idea about dissolving sugar in water. The sugar dissolves, and the ‘sweetness’ becomes free. Other examples are related to properties like colour, magnetism or weight (Steffensky et al., 2005).

In contradiction to these results, Butts and Smith (1987) found out that high school students are able to interpret physical properties of matter like hardness and different melting points based on a particulate model of matter. Especially in the case of melting points they draw reference to the force between particles. In the case of high melting points (e.g. sodium chloride), the ‘bonding’ between the particles are suspected of being stronger than in substances with lower melting points (in the interviews carried out by Butts and Smith, this substance was sugar). Regarding the concept of micro–macro thinking, this is another steppingstone for learning: When properties are not related to substances, they will not be related to structures either. The researchers of that time, and possibly also many students today, were not interested in explaining properties, they were only aiming at mixing them to produce the substance they were aiming for, e.g. gold. To do so, they did not even need a microscopic level. If this is the same for students, they might also be satisfied with observing substances without explaining their behaviour. This period of time can therefore be regarded as a step back in micro–macro thinking, but knowing the reasons and background theories of alchemists can be very helpful to interpret students' thinking nowadays. However, in respect of the results by Butts and Smith, one should be careful to underestimate students' chemical reasoning skills. The 'substantialisation' scheme appears mostly for properties which are difficult to explain. The taste of artificial sweeteners, for example, needs quite complex explanation via molecular shape and recognition of the molecule in the receptor sites. Magnetism is even more difficult to explain. Maybe, not all students' expressions which sound like substantialisation are really based on non-atomist thinking. Could some of them just be a metaphor or a paraphrase to explain something, they just can't explain?

Ionic Bonding

Historical Development

Within and after the scientific renaissance between 1400 and 1600 two events happened which were central for the further development of science. Following Petracas motto '*ad fontes*', scientists rediscovered on the one hand the material theories of Greek and Roman philosophers – in 1417 the poem by Lucrez '*de rerum naturae*' had been rediscovered – the idea of atomism came again into scientific discourse. On the other hand, scientists began to develop the methods of today's science. Breaking with the scholastic thinking of the middle ages, Roger Bacon and others proposed more empirical ways to develop knowledge and truth including hypothesis, experiments and conclusions (Gloy, 1995). With the development of modern science, scientists started to build links between micro and macro levels by real models. Their ideas became more sophisticated including results from physical measurements and mathematical models of the shape, arrangement and properties of particles.

One of the intensively discussed topics was the question about the shape of atoms – a question with also high educational relevance, if we think of some students' preconceptions. We can focus on two main positions: One group of chemists observed that crystals always broke to parts with similar shapes to those of the original crystal. Therefore, their theory was that the smallest particles of atoms must have also the same shape as the macroscopic crystal. If we follow Domenico Guglielmini (1655–1710), the particles of sodium chloride would be cubic, those of calcspar would be triclinic. Hexagonal-prismatic and trigonal-prismatic crystals would contain trigonal particles. Another theory was formulated by Nicolas Lémery (1645–1715). According to his theory, the smallest particles of acids would have sharp edges, because the salts of many acids crystallise to needle-shaped crystals and cause pain like needles in the mouth. René Just Haüy (1743–1822), a French mineralogist of the eighteenth century, also postulated the idea of cubic or otherwise shaped particles (the primitive form), but in his theory the sides of octahedral crystals and other faceted crystal layers were not caused by octahedral particles, but by diminishing layers of particles (Fig. 10.3).

All those theories have in common that they postulated a continuous model of matter. Here, continuity does not mean the denial of a particulate model, but the particles were arranged without gaps between them, so that space was continuously filled with matter: following the idea of ‘horror vacui’, there was no open space between the particles. In all three theories, the smallest particles lay close to each other without leaving a gap between them. The arguments of these theories were mostly influenced by geometrical reasoning about the shape and splitting of crystals.

Although those theories of cubic particles have great potential to explain the shape of crystals, they had some problems that were not easily solved: it is not possible to arrange octahedral particles without gaps, so that it failed to explain the shape of octahedral crystals like potassium alum. Furthermore, it was difficult to interpret chemical reactions with such a model. Here, this theory failed. Robert Hooke (1635–1703), Robert Boyle (1627–1691) and William Hyde Wollaston (1766–1828) developed a model of ball-shaped particles as smallest particles of matter which can be arranged in various forms. This theory had, compared with the theory of cubic particles, two advantages: It was consistent concerning different shapes of crystals and chemical reaction was easy to interpret as new arrangements of atoms. Processes like mixing and solving were interpreted as intercalation of solvent molecules in the gaps between the particles. However, without refined physical data, both theories were mere philosophy.

At the beginning of the nineteenth century, chemists and physicists started making detailed measurements about the physical properties of crystals. Among others, Moritz-Ludwig Frankenheim (1801–1869) investigated systematically the hardness, splitting, optical and acoustical properties, and thermal expansion, of different crystals. He concluded from his results that a model of matter with gaps between the smallest particles would be able to explain his measurements in a better way. Anyhow, the decision between those two models was more a lawsuit of circumstantial

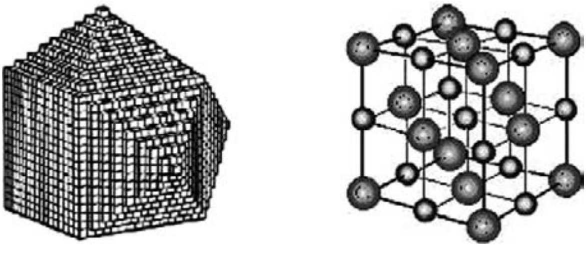


Fig. 10.3 Ideas concerning crystals: *left* the continuous model of Haüy with cubic particles, *right* the nowadays model of ionic lattice

evidence: Both sides lacked a real positive proof for their theory. This ‘smoking gun’ was found in 1912 by Max von Laue (1879–1960), who could prove the lattice theory using x-ray diffraction (Groth, 1979; von Laue, 1912). This proof is a good example to show the necessity of specific empirical methods for further developments in or convincing arguments about theories.

The historical progression of ideas was considerably different from that followed in educational settings. Ludwig August Seeber (1824) concluded from physical data that the discontinuous model of matter was more appropriate to explain reality than the continuous model and carefully delimited the properties of a chemical bonding. He suggested two forces: The particles were hold together by an attractive force. A repellent force would hold them in a certain distance from each other. He called the attractive force ‘positive’, the other one ‘negative’. The particles find their place as both forces are in equilibrium. This model explains a lot of physical properties of crystals like hardness and elasticity. Also, the different density of minerals is easy to interpret if we presume different intensity of the opposing forces between different particles so that the point of equilibrium varies. With the formulation of these outline data, Seeber had made an important step in the direction of a ‘microphysical’ model of crystals (Weißbach, 1971). Without any information about the character of these forces, no real link between macroscopic and microscopic properties would be possible.

Further efforts have been made to answer the question about the character of these positive and negative forces. On the one hand, researchers made important progress in the field of descriptive crystallography. In 1822, the mineralogist Friedrich Mohs (1773–1839) developed a system of 32 crystallographic classes. Two years later, Seeber deduced a system of mathematical space lattices, whose grid points indicate the place of the smallest particles. In 1850, Auguste Bravais (1811–1863) deduced the 14 primitive crystal lattices. This was the basis for the works of Schoenfließ und Fedorov, who derived in 1891 mathematically the system of 230 space groups, which explain the geometrical properties of crystals (Groth, 1979). On the other hand, knowledge about the chemical bond grew steadily. Michael Faraday (1791–1867) showed that substances disintegrate under the influence of an electric current. One part was attracted by the positive pole, the other by the negative pole. From these results, the Swedish chemist Jöns Jacob Berzelius (1779–1848) concluded that the particles of such substances must be attracted by electrostatic forces. But still some questions remained: Are the charged particles free or does the electric current force them to separate? In this time, most chemists preferred the second idea: Two particles attract each other, and separate only under the influence of electric current. It was Svante Arrhenius (1859–1927) who could prove with the help of kryoscopic methods that ions are free (but solvated) in solutions. But was it possible to extrapolate the results to the solid phase? If the theory of crystal lattices was right, what were the particles on the lattice grids, single ions or ion pairs?

The German physicist Erwin Madelung (1881–1972) found an answer to this question in 1909. Madelung investigated the absorption of crystals in the infrared spectrum. For many crystals, there were already absorption spectra available.

Madelung (1909) tried to explain the absorption based on the (still unproven) lattice model suggesting a vibration of ions. Data about the bonding enthalpies between the ions were accessible via calorimetry. Madelung used this bonding energy to calculate the vibrational frequency of the ions around their theoretical rest position in the lattice. He found out that the observed absorption and the predicted vibration energy are almost equal. In a second step, he concluded from the vibrational frequency on the ionic charge which was the same as the already known valencies. Based on these results, Madelung developed the model of ionic bonding and ionic lattices. This relationship between the absorption bands and the ionic lattice is – as Madelung writes – the first proved relationship between microscopic and optical properties of crystals.

Madelung's proof of the hypothesis of space lattices was an indirect one. The direct proof was made in 1912 by Max von Laue, who used two conjectures as a starting point for his experiment. The first conjecture concerned the newly discovered x-rays, whose wave length was estimated in the range between 12 nm and 5 pm. The other conjecture concerned the distance between the lattice planes. Based on these two conjectures he built the hypothesis that the interaction x-rays with crystal lattices should lead to interference, what he could show in experiments.

Students' Ideas in Comparison

As the results of Pfundt (1981), Griffith (1987) and Lee et al. (1993) show, students have problems in dealing with the idea of empty spaces between particles. In her studies, Pfundt presented students with different representations of atoms. The students had to choose the one that represented their ideas at best. Numerous students chose representations of cubic or hexagonal atoms, because 'they fit without gaps between them' (Pfundt, 1981, p. 87). Griffith and Preston (1992) could explicitly show that students suppose that the size of a crystal corresponded to the shape of its atoms. Furthermore, they discuss the parallels between this students' conception and the corresponding historical idea of René Haüy.

Until the beginning of the nineteenth century, scientific researchers did not consider the question of the forces between particles. For students, however, this question seems to be quite apparent, although a lot of misunderstandings impede learning about chemical bonding (Taber, 1994; Bello et al., 2007; Özmen, 2004). In the studies of Butts and Smith (1987), students compared, in an experiment, the melting points of different crystalline substances like sugar and sodium chloride. As expected, sodium chloride had a much higher melting point than sugar. Asked for an explanation for this phenomenon, the students guessed that the chemical bonding in the salt must be more stable than in sugar. Looking at these ideas, it will be interesting to have a closer look at the genesis of our current knowledge about chemical bonding in crystals.

In the classroom, ionic bonding is mostly introduced by the example of simple ionic substances like sodium chloride. Starting from the electronic configuration of the atoms, the students conclude that one electron jumped to the other atom, and both reach a full outer shell of electrons. This (usual) way leads to several misunderstandings. Taber (1994) and later on Barke (2006) could show that numerous students misinterpret the particles of sodium chloride as pairs and not as single ions. The six rods in the commonly used model of the sodium chloride lattice are seen as one ‘chemical’ and five less specified ‘physical’ bonds.

What implications for teaching can be drawn from students’ views and these historical considerations? At school we often try to convince students to use a present-day scientific theory without offering them an insight into the often complicated methods of investigation and into the two-way interaction between the development of theories and empirical methods. Consequently, it must not be surprising that we find many students with concepts in mind that are alternative to those that scientists and teachers offer them.

With regard to the results of Taber (1991, mentioned above), Barke (2006) suggested that these students’ conceptions could be ‘home made’, a conception caused by misunderstandings in teaching the ionic bonding. As the view of the history of science shows, it seems to be possible to learn a lot about the chemistry and the physical properties of crystals and salts without the model of ionic bonding. According to Taber’s (1991) results, the model seems to be difficult to understand, so maybe these conceptions may be better introduced later in the students’ curriculum. It could be a convenient approach to follow the historical development: In a first step, students could learn about the properties of the ionic lattices and afterwards explain their nature and genesis. Also, teachers have to consider the complexity and the interaction of the many different parallel research studies and outcomes in different fields of chemistry as described above. Only the linkage of such different interpretations finally may lead to a convincing theory. Why should we expect an easy development of a parallel conceptual understanding by students, who often are presented with only *one* experiment in a short period of time?

Covalent Bonding and Organic Chemistry

Historical Development

In the early development of organic chemistry, researchers thought that the properties of substances would mainly be determined by the *sort* of atoms involved. After chemists had made progress in the field of elementary analysis, it became possible, to ‘count’ the particles in organic compounds. It was Justus von Liebig (1803–1873) in 1832 who found the first hint of the importance of the arrangement of atoms in determining the properties of matter. Liebig was working at the elementary analysis of cyanic acid and fulminic acid and found out that they each have one atom of hydrogen, nitrogen, oxygen and carbon. In other words: Both acids had exactly the same atomic composition, but completely different properties. Fulminic acid is highly explosive, cyanic acid not. After several re-investigations and other examples of substances with the same atomic composition but different properties, Berzelius interpreted this phenomenon as meaning that the atoms in the two substances must ‘combine in such different ways’, so that the resulting substance had completely different physical and chemical properties. He called the new discovered phenomenon isomerism (Berzelius, 1832, p. 310). Not only the kind of atoms, but also their arrangement seemed to be important for the properties of a substance.

The relevance of the arrangement of atoms was confirmed by a discovery by the French chemist Jean André Dumas (1800–1884). Dumas demonstrated in 1839 for the example of acetic acid, that some hydrogen atoms can be substituted by chlorine without a change in the main properties of the substance. Acetic acid and chloroacetic acid are both acids, only the strength is different. His observations were summarised in the ‘theory of substitution’, where he postulated, that the properties of matter are mainly influenced by the arrangement and not by the sort of atoms (Dumas, 1833, p. 288). The ‘arrangement’ of atoms was later renamed as ‘chemical structure’. Therefore, the discovery of isomerism and the ‘theory of substitutions’ can be regarded as the beginning of organic structural chemistry. Breaking with Berzelius’ dictum, who said that the properties were mainly based on the properties of atoms, Dumas wrote with certain acrimony:

> It is not necessary to let Mr. Berzelius know, that, according to the views of electrochemistry, it is mainly the n*ature* of the elementary particles which determine the main properties of matter. According to the theory of substitutions, however, the properties of matter are mainly determined by the *arrangement* of particles (Dumas, 1833, p. 288).

With this idea, a completely new element was introduced in micro–macro thinking: the term ‘arrangement of particles’ was later called the *chemical structure*.

For a real structural determination, further theoretical background was needed. August Kekulé was the first who thought about this background in 1858. He suggested that the reaction of two organic substances means on the microscopical level a kind of an exchange of parts of the molecule. The molecules must come in close contact, existing bonds must break and new bonds have to be built. Based on this theory, Alexander Butlerow (1828–1886) introduced a new principle in organic chemistry in 1861. According to him, in a chemical reaction the number of atoms changing their place should be as small as possible. Based on this principle, it should be theoretically possible to detect a certain chemical structure by the help of specific reactions. If a chemical reaction was accompanied by a complete rearrangement of atoms (as mostly in inorganic chemistry), a structural determination with specific reactions would fail. With these premises in mind, chemists could start to develop specific reaction to identify reactive groups.

A typical example for Butlerow’s work is his investigation about the structure and the reactivity of ethanol. The question was in a chemical reaction are the hydrogen atoms substituted at the CH_3- or at the CH_2OH- side of the molecule? To answer this question, he methylated ethanol. If the substitution would take place at the CH_3-side, propanol would be generated, otherwise isopropanol. Both substances show different boiling points. The product showed the boiling point of the secondary alcohol, which could by proven by oxidation to acetone. This theory was another milestone in the development of micro–macro thinking: a theory that could make a link between the reaction of substances (and therefore dynamic properties) and the arrangement of atoms. Secondly, ideas about structure could now been tested. In other words: Butlerow invented the first possibilities, not only to speculate about microscopic structures, but to investigate them.

Although huge efforts had been made in the field of structure determination, the question about the spatial arrangement of atoms remained. In 1848, Louis Pasteur (1822–1892) made a discovery that gave the first hints of an answer to that question. Crystallising tartaric acid, he observed two different types of crystals with identical, but mirrored, shape. He separated the crystals and determined the rotation of polarised light of the solution, which was different, too. He concluded that the difference was not only a crystallographic effect, it also affected the molecules themselves: The molecules themselves must be asymmetrical. Pasteur speculated about at tetrahedral arrangement of substituents around a central carbon atom, but he had no possibility to prove his idea. It was Jacobus Hendricus van't Hoff (1852–1911), who combined all those results to an all-embracing theory. The theory about the 'arrangement of atoms in space' was published in 1908 and explained the most results concerning stereoisomeric substances. Here, he developed the basis for our nowadays theory about the geometry of molecules.

So far, results about the shape of molecules had mostly been reported. Chemical (covalent) bonding, however, was considered much less extensively. A theory of covalent bonding was developed in 1916 by Gilbert Newton Lewis (1875–1946) and Walter Kossel (1888–1956). At this time, research about the structure of atoms had made huge steps forward. Max Planck had developed the quantum theory in 1900, and with the application of the theory on the electronic structure of atoms, the theory of valences got a theoretical groundwork. Lewis deduced the octet rule in 1916 and developed (mostly intuitively) the theory of covalent bonding. Walter Heitler (1904–1981), Fritz London (1900–1954), John Slater (1900–1976) and Linus Pauling (1901–1994) managed in 1927 to confirm Lewis' conjecture by quantum physical calculations.

The knowledge about the mechanism of chemical bonding is essential for understanding the chemistry of molecules, but it does not explain much of their physical properties. Or, expressed in another way: Much was known about microscopic properties of atoms and molecules. Much was known as well about the properties of molecules. What was still missing was a real linking theory between macroscopic and microscopic properties. Physical properties are mostly dependent on special forces, the van-der-Waals forces, and the hydrogen bonds between them. Johannes Diderik van-der-Waals mostly investigated the change between the different states of aggregation. He postulated the theory that all states of aggregates can be described using the same forces. In his theory, states of aggregation are only points in a continuous spectrum of interaction between the movement of molecules and the forces between them. Furthermore, he was able to explain other physical phenomena like viscosity or adhesion and cohesion of liquids – all dependent from intramolecular forces. But what was exactly the nature of these forces? Which chemical structures were responsible for the macroscopic behaviour of molecular substances? Van-der-Waals-forces can be differentiated in *Keesom*-forces between two dipoles, the *Debye*-forces between a dipole and an ion and the *London*-forces between two apolar molecules. Furthermore, hydrogen bonding influence the physical properties of matter dramatically.

One important structure in molecules are polar bonds and, as a result, polar molecules. The polarity of molecules had been first formulated by the Dutch physicist Peter Debye (1884–1966) in 1912, as he tried to build a microphysical model to explain dielectricity (the behaviour of an electric field in a substance). Later, he related the polarity of molecules to the interaction between molecules and ions. Together with Erich Hückel he succeeded in formulating a complete theory about the behaviour of electrolytes (Hoffmann, 2006). The discovery of the dipole moment caused high efforts in the research on physical chemistry. On the one hand, methods for determining the dipole moment were developed. On the other hand, the correlation between the shape of the molecule and its dipole moment was investigated (Estermann, 1929; Errera & Sherrill, 1929).

Based on these results, the attraction between polar molecules was quite easy to explain. Willem Hendrik Keesom (1879–1956) presented a mathematical description of these forces in 1921. The so-called *Keesom*-forces are often used to explain the boiling points and the viscosity of polar substances without hydrogen bridges. Apolar regions in molecules also are able to interact physically and are another important structure to judge the properties of substances. In the history of science, these interactions caused great difficulties when researchers tried to explain these rather weak, but significantly measurable forces. Although it was already possible to liquify noble gases, the weak forces between them stayed quite obscure, until Fritz London and Walter Heitler (1904–1981) found an explanation in 1927. Based on quantum physical calculations they found that attracting forces are not caused by electrostatic attractions, but by quantum mechanical floating (Heitler & London, 1927).

The third important structures are polar O–H- or N–H-groups in molecules, predestined to build hydrogen bonds which are important for the explanation of the properties of a substance. The concept of hydrogen bonding was postulated by Maurice Huggins (1897–1982) in 1919 in his dissertation. In 1936, he successfully developed and applied this concept to explain the crystal structure of ice and the melting and boiling trends of several organic substances (Huggins, 1936).

With these theories, the theoretical gap in the explanation of physical properties was closed and scientific micro–macro thinking was set on a firm empirical basis. Further investigations refined the theories, but the main guidelines were laid.

Students' Ideas in Comparison

This explanation of states of aggregation was much later in the history of science than it is in most curricula. In science education, it is usually a topic of the first year of learning chemistry (age groups 12–13). The shape of molecules has a vast influence on their polarity and therefore on the forces between them. However, students of this age and experience have great problems in estimating the influence of different parameters on the polarity. In a study by Peterson, Treagust, and Garnett (1989), only 13% of the students in 11th grade managed to predict the shape of NBr_3 correctly and only 38% in the 12th grade. Regarding influential parameters on the shape of molecules, students suggested three factors: Some mentioned the polarity of the bond, others mentioned double bonds and 22% referred to the repulsion of binding electron pairs, but ignored the influence of the non-binding electron pairs. Others did not take into account the different values of electronegativity. The students' ability to predict the polarity of molecules based on their shape is fairly low.

We also find students' conceptual ideas documented for other physical properties, such as viscosity. In their study, Peterson et al. (1989) asked students to give reasons for the viscosity of Vaseline. Twenty-seven percent of the students argued about the covalent network in the substance. They thought that the change of shape correlated with the breaking of bonds between atoms (which, of course, would mean that a chemical reaction would have taken place). Soft substances were given weak bonds so that these substances were able to adapt their shape. Another 37% gave the correct answer of weak intermolecular forces between the particles, so that the shape of the substances could easily been changed.

Schmidt's (1992) investigation of students' conceptions (12th grade) concerning isomerism showed that students mostly regard substances from the same material type (acids, ethers) as isomers; n-propanol and isopropanol, for example, are regarded as isomers, whereas propanol and ethyl-methylether are not considered to be isomers. In contrast to Schmidt's hypotheses, the shape (rod-like, cross-shaped) of the molecules was not so important for their choice.

Peterson, Treagust, und Garnett (1989) and Furio et al. (2000) investigated the conceptions of 12th graders concerning chemical bonding and polarity, intermolecular forces and the octet rule. Some students suggested the number of possible bonds of atoms is the same as the number of its valence electrons. According to this theory, nitrogen atoms would have five bonds. Here, a chronological view on the theories could help to delimit their 'omnipotence' and to prevent such misunderstandings.

The connections between historical ideas and students conceptions or learning difficulties are less close for this than for other topics. Three points may be mentioned as possible causes. Firstly, the context and problems that lead to the development of these theories are mostly 'scientific' problems. Dielectricity and the coherence of apolar molecules are phenomena which are only a problem in a specific scientific context. Secondly, the knowledge base, where such scientific theories are founded, grows exponentially and gets canonised in the university as a central institution of knowledge storage, development and transfer. Thirdly, the methods of investigations (apparatus, infrastructure and scientific language) got more and more complicated. Therefore, the ideas of scientists are less based on primary experience or observations, but more on scientifically lead and filtered observations. Thus, if compared to ancient scientists, the gap between students and scientists widens.

Macromolecular Chemistry

Historical Development

Even though the historic development of macromolecular chemistry parallels that of the history of organic chemistry in general, the teaching and learning of this area at school generally starts after an introduction into the basic principles of general organic chemistry. Macromolecular substances produced by living organism have always played an important role in the life of human beings. Some substances were used to build houses, others to produce clothes and again others were used as food. However, the microscopic structure was undetected for a long time due to the absence of suitable experimental methods of analysis (Simon, 1950). One of the first ideas to explain the elasticity of substances came from Nicolas Lémery who thought that the particles of elastic substances had a structure like springs and were thereby elastic. So again, Lémery transferred the properties of substances onto particles, as many students do.

Another area of research with potential industrial purposes began with the idea of using the juice of the rubber tree in Europe. As this liquid coagulated during lengthy travel, a suitable solvent had to be found, namely, naphtha, a light fraction of oil (Elias, 1985). However, this process seemed to be incomplete as the liquid stayed milky. Similar observations were made with other substances, like starch, which are now known to be polymers. People at the end of the nineteenth century explained this phenomenon by small aggregates of molecules that scatter the light. These aggregates were called micells. Substances that were not solved completely were called colloid substances (glue-like substances). The chemists of that time did not have the idea that these ‘micells’ could be huge molecules because the theory of micells was sufficient to explain different properties, such as the swelling of substances. The biologist Nägeli (1817–1891) for example thought that water gets between the micells so that they would get pressed away from each other. For fibrous substances he postulated micells arranged in rows. Other developing theories and methods in chemistry also did not change the theory of micells. One important method was the analysis of the number of particles in a solution with cyroscopic methods, which were again regarded as micelles. Hermann Mark (1895–1992) and Kurt Meyer (1893–1952) analysed cellulose and caoutchouk by x-ray diffraction. The spectra of cellulose showed a large number of elementary cells. They interpreted this result with the idea of aggregates of molecules and proposed ‘secondary valences’ as bonding. ‘Secondary valences’ were regarded as weaker bonds compared to the main bonds of the carbon-chains. But even 100 years after Nägeli, macromolecular substances were regarded as built by micells. However, chemists tried to analyse and to interpret such micells in more detail.

In the case of caoutchouk, it was suggested that the short chains were attributed to the presence of many double bonds. Under mechanical forces, they are stretched like a spring that causes the mechanical properties of caoutchouk. This theory was supported by results from x-ray diffraction: stretched, caoutchouk showed sharp diffractions, which instantly disappeared under relaxation. Changes in the physical properties of synthetic substances were explained by changes in the bonding between the micells. The process of vulcanisation, for example, was explained by the formation of disulphide bridges between the micells, which leads to higher mechanical stability (Priesner, 1980).

Only one theory was proposed in opposition to the theory of micells: Hermann Staudinger (1881–1956) developed his theory of macromolecules in the 1920s. Staudinger's theory was somehow revolutionary as it broke with the former idea of molecules as small particles of exactly definable size. He explained the scattering of light in colloid solutions by huge molecules instead of aggregates of smaller molecules. One important method to prove his theory was the reaction of adding hydrogen to double bonds, for example of isoprene in caoutchouk. In case of micells, there should be no bonds and valences between the micells left after adding hydrogen in excess. The solution should become clear as the micells should drift away from each other. However, the experiments showed something different: the solution stayed colloid and milky. These results were one important step forward to the theory of macromolecules. In his further research, Staudinger (1961) investigated the influence of side chains on the melting points of polymers and the viscosity of their solutions. Through syntheses of polymers, he could show that fibrous substances were also built by macromolecules and not by strings of micells.

The same observations at the macroscopic level can lead to different interpretations of the microscopic level. Why was the (more complicated) micellar theory so successful? The reasons for the final success of the macromolecular theory are still unclear. Staudinger broke with the former definition of the term 'molecule' as a limited aggregation of definite size. Staudinger's molecules showed changing molecular weights and were bigger than anyone could imagine a molecule could be. All other methods of investigation like x-ray diffraction, swelling of polymers, scattering of light in solutions etc. showed results which could be interpreted both in the sense of macromolecular and micellar theory (Table 10.2).

Table 10.2 Comparison of properties of small molecules, colloids and polymers by Staudinger (1961)

Properties	Small molecules	Linear polymers	Eucolloids
Solubility	Without swelling	Compared by swelling	Compared by swelling
Dissolved particles are . . .	Monomers	Polymers	Polymers
Viscosity of a 1% solution	Low	High	High
If the colloid properties of the solution change . . .	No change in molecules	Degradation of macromolecules	No change in molecules, but the size of the micelles change

This leads us to a crucial point in thinking about micro–macro relations: The closeness of the linkage between the microscopic and the macroscopic view of the world. As the example of the macromolecular theory shows, the same observations can be explained by different theories. In other words, the connection between phenomena and scientific theories is not an unambiguous one. Although one theory fits better with the observed facts than the other, the construction of the model always remains a theoretical *construction* to explain phenomena. On the other hand, theories can influence the macroscopic ‘reality’ as well. The polymer theory, for example, can be used to *design* polymers.

The discussion between these two theories of micelles and macromolecules seems to be interesting for educational purposes. Students can see that a change of theory is often a long drawn out process which is not only fought by scientific arguments but also by polemic statements and disputes. In this way, students have an insight into the discourse of science. Additionally, the students can realise that experimental results can be interpreted differently but consistently with different theories, as neither of the two theories enabled significant explanatory clues from the macro-level onto the micro-level. They can also see, in the further development of polymer science, that science and technology, theory and phenomena are closely interrelated and influence each other.

Students’ Ideas in Comparison

No studies have apparently been published yet into students’ ideas about polymers. Our study presented later gives some first hints; for the sake of completeness the main results are sketched here. Younger students without knowledge about molecules tend to explain hardness and density of polymers by different densities of atomic packings. Students from 12th grade who already had learned about polymers used the denseness of covalent network in polymers to explain their mechanical properties. Other studies (Bigalski, 2005) showed that the ‘denseness of a covalent network’ seems to be a plausible concept for students. Here, students from 9th grade were asked to relate different materials (rubber, hard plastics etc.) to structural representations. Even though the students had no knowledge about polymers, most students selected the right structural formula. These students’ conceptions show no relation to historical ideas: Possible reasons had already been outlined.

Investigating the Educational Effects of Historical Ideas

Despite these hopes and ideas, the amount of concrete teaching material available is fairly low. Some synoptic and carefully commented presentations of historical debates (e.g. Minssen & Walgenbach, 1985) and some teaching units are available (for example Jansen et al., 1995; Matuschek & Jansen, 1985; Masson & Vazquez-

Abad, 2006; Craft & Miller, 2007). Nevertheless, there is a great lack of tested and evaluated material and teaching experience, especially concerning conceptual change and the debates about the nature of science (NOS) in science education where little attention had been paid to the development and evaluation of sophisticated teaching units.

Furthermore, Wehlen (2006) showed that the representation of the history of science in schoolbooks is rather poor and the books seldom take into account the above mentioned theoretical positions. However, a representation of scientific debate is the basis for the social constructivist view of science (e.g. Jansen & Matuschek, 1985; Lederman, 2004; Höttecke, 2004). Other representations of single scientists may lead to a glorification of a single scientist, again leading to an authoritative view on science in general. According to Höttecke (2004), only a few students know about the discursive character of science, involving the possibility for students to participate as responsible citizens, which is a *conditio sine qua non* for developing critical thinking in classroom.

How can students articulate their preconceptions in the classroom freely? Several techniques are known like drawings, mapping techniques and open discussions. Another idea is the use of concept cartoons. In this approach, persons with different opinions (which maybe show similarities to students' conceptions) are depicted. The students can use these opinions as a starting point to discuss their own opinions in classroom (Keogh & Naylor, 1999). Such cartoons can also be designed by using historical ideas as impulses to initiate students to think about their own conceptual explanations.

How can the similarities we described above be used in classroom teaching? We would propose the following, quite pragmatic model:

1. The teacher hands out historical, but for educational purposes reduced, material to the students that presumably will pick up students conceptions and actual scientific positions. This material could be short texts, graphics, extracts from letters or compendious worksheets presenting several contradictory positions of different researchers.
2. The students discuss these ideas and propose experiments to verify or falsify one of the presented theories. From a methodical point of view, several approaches from discussions, poster presentations up to actual role-plays are possible. The students have the possibility to choose one of the scientists as an advocate for their preconceptions. Using this technique, it will be easier for the students to express and defend their conception in classroom.
3. Based on the experiments and if necessary on additional material, the pros and cons for either of the theory shall be collected and discussed. If possible, a decision should be formulated and explained.

Arguments against this rather simple way of proceeding can be based on the fact that the history of chemistry is simplified too far in order to produce suitable teaching material. Scientific developments are ripped out of their historical context and sometimes rudely simplified. Other concepts, like the historical problem-centred concept (Jansen et al., 1995; Jansen & Matuschek, 1985) or the historical-genetic concept according to Pukies (1979) are far more interested in a ‘realistic’ understanding of the historical gain of knowledge or in learning about the nature of science. Rudge and Howe (2004) present a proceeding of four steps: (1) Identifying an prioritising the objectives of the teaching unit based on curricula and national standards, (2) selecting an episode, (3) preparing teaching material (4) implementation in the classroom. The helpful (though not quite sophisticated) scheme by Rudge and Howe pays no attention to students’ conceptions. Also the more elaborated conceptions by Jansen et al. (1995) and Pukies (1979) make nearly no reference to this important point – the identification with historical researchers is here a more affective and less seen under a conceptual change perspective.

Through this chapter we would like to express our appreciation of all these educational concepts. Besides (not in contrast) the conceptions mentioned above, *our* intention is to initialise a process of reflection and maybe of conceptual change for the learners. Learning about the history of science into more detail can be a desired ‘by-product’, but it is not the main focus of the approach described above. Therefore, it is our aim to promote learning about basic processes in chemical enquiry, whereas the other projects mainly focused on learning about single topic or phase in the history of chemistry.

Following the analyses described above and the guidelines of the Model of Educational Reconstruction, we have designed an exploratory, qualitative, study to investigate students’ ideas and discussions working with exemplary historic material. We carried out 15 teaching experiments with students aged 14–18 years. The younger ones, who had just started their chemistry courses, were given material on crystals. The older students were working on material about polymers. Of course, the students’ answers cannot be compared directly because of the different topics, and an analysis of the students’ conceptual explanations was not the key focus of the study. We rather wanted to investigate whether and how historical ideas could provoke the students to discuss their own ideas, to compare pros and cons of different theories and to take different reasons and perspectives into consideration. To do so, we needed a topic that the students had not already dealt with at school, therefore we chose different topics for different age groups.

Salts and polymers were chosen because of their daily-life applications and presence and because of their interesting and diverse historical background. The structured interviews each lasted about 40 minutes and were carried out with pairs of students to encourage discussion. Every interview began with a demonstration of a certain property of the material or with an experiment (Table 10.3). The students were asked to explain the phenomena on the particle level. Although the 7th graders were not taught about the particulate concept of matter in school, they did not hesitate to argue based on their ideas about smallest particles. After this introduction, the students were given historic explanations through texts and drawings (Fig. 10.2). They were asked to discuss the different positions, to evaluate them and, if possible, to suggest experiments which might be helpful to find out which theory might be more suitable (Figs. 10.4, 10.5 and 10.6).

Table 10.3 Experiments and historical episodes used in the teaching experiments

Topic and age group	Experiments and phenomena	Historic theories as impulses
14-year-olds: crystals	Observation of different crystals (Copper sulphate, calcspar)	Theory of hooks and eyes by Leukipp and Demokrit (drawing)
	Splitting of crystals	Theory of Haüy (original picture)
	Shape of crystals (sodium chloride and calcspar)	Theory of Hooke (original piture)
		Nowadays model of an ionic lattice
16–18-year-olds: polymers	Observation of different polymers (phenolic resin, polyethylene, polystyrene)	Theory of micells by Mark and Meyer
	Tyndall's effect	Theory of polymers by Staudinger
	Physical properties of polymers	
	Swelling of starch and SAP	

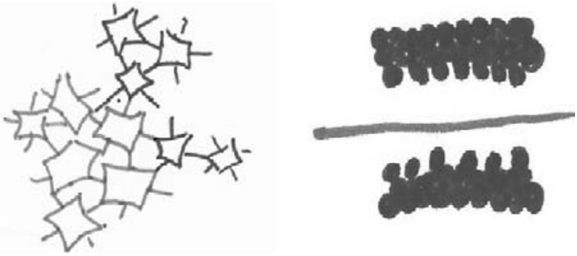


Fig. 10.4 Drawings of students (7th grade) about their ideas of atoms in crystals. *Left*, angled particles with 'bondings' between them, *right* ball-shaped particles in closest arrangement. The line in the middle indicated a possible breaking edge

Fig. 10.5 Theories about the constitution of 'polymer materials'. *Left* the theory of micells by Mark and Meyer (1928) at the example of cellulose, *right* Herrmann Staudinger with a model of a polymer chain

Interviews on the Particle Structure of Crystals

All interviews were audio-taped and transcribed. Following a simplified scheme of Mayring (2000), the answers and discussions were then analysed and categorised.

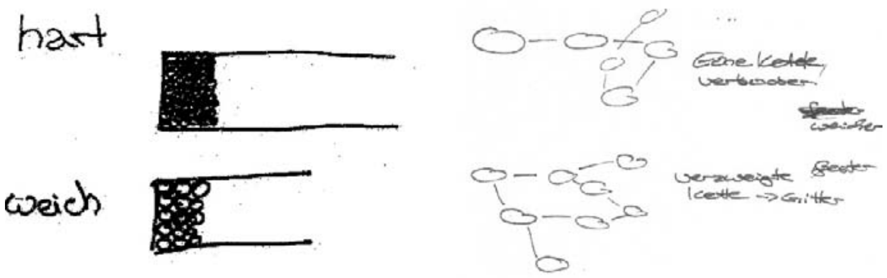


Fig. 10.6 Drawings of students about their ideas of hard and soft polymer materials. *Left*, a student (7th grade) argues with the closeness of the arrangement of particles. *On the right* a student from 12th grade. The difference is caused in the closeness of the covalent network

When asked to describe and to explain the properties of crystals, all the students immediately used ideas of particles, even though they had not been taught these ideas at school before. In contrast to the historical researchers, who set their focus on the shape of crystals, the students mainly described and explained properties such as the hardness or the colour of crystals. The concept most used by students was the density of package of the particles. According to the students' explanations, the lighter and the less stable a material was, the smaller was its density,.

Regarding the historic explanations, the students were neither convinced by the idea of hooks and eyes (Leukipp, Demokrit), nor by the idea of cubic particles (Haüy). However, the historic arguments were used by the students to discuss their own ideas of bonds between the particles and to discuss the cubic shape of some crystals.

To enhance the discussion even further, we showed them pictures of cleaving a crystal. Such experiments played an important part in the history of theory development in the area of crystal chemistry (see above). The students were able to draw the conclusion that splitting must be correlated to a separation of particles, but they did not draw any conclusions about the shape and order of the particles before and after the splitting.

In general, this explorative study confirmed the usefulness of historical approaches to enhance students' discussions and reflections about their own ideas. The pairs often came into a dialogue about suitable and unsuitable theories and tried to find arguments pro or against the one or the other. Typical preconceptions like the brick-like arrangement of atoms were not found.

Interviews on the Structures of Polymers

Polymers are not only an important topic of chemistry because of their many applications in everybody's daily-life, they are also interesting because of the theories that can be applied to explain and to design polymers and their properties. However, the teaching experiments and interviews gave hints that the historical development of theories to explain polymers and the students' explanations are not as coherent as for other topics. One reason might be the fact that students, especially younger students, do not separate between different classes of substances systematically. They tend to use the same explanations of all phenomena and might not see the special properties and the need for a special explanation for polymers. This had been the case for researchers in the past, who had the challenge of explaining properties: this was not easy using the accepted theory of molecules only having a limited number of atoms.

The younger students, who had not been taught organic chemistry before, mainly used the idea of the density of particles again to explain the hardness of polymers. The concept of density seems to be a ‘general explanation’ for almost all phenomena, as other studies have found. The upper secondary students, who had been taught aspects of organic chemistry, used the grade of density of the covalent network to explain the different properties of the given polymers. The hardness of polymers was explained by more covalent bonding.

Given the two theories of Mark and Meyer, and of Staudinger, the students evaluated both theories as being convincing and could not really see the differences between the two. Again for these students, the revolutionary idea of Staudinger, which changed the general idea of molecules at that time, was not unusual, even though they had also learned at school that molecules have a certain number of atoms and build a unit. Still, the students were obviously not used to discussing theories and different concepts of explanation. Some students also had no problems in using both theories at the same time, one to explain soft polymers (the theory of micells with weak forces between the micells) and the other one to explain hard polymers (the theory of molecules with stronger bonding). The parallel use of different concepts has been found in other studies too (Nieswandt, Schmidt, & Parchmann, 2001). However, the students were able to connect and to change between the macroscopic level and sub-microscopic explanations and to draw conclusions and hypotheses from one level to the other.

After these first explanations and discussions, the students were shown some experiments. The explanations were diverse: Some students explained the swelling of SAP as a chemical reaction, not as an uptake of water between the polymer structures. The demonstration of the Tyndall effect was also not helpful to evaluate the two theories in a better way, as both were used again as explanations.

In summary, the historical material about polymers was not as fruitful in the way we used it. Both theories seemed to be useful and convincing for the students. Obviously, both theories are complex and could indeed explain the observed phenomena. The need for modern techniques of analyses becomes obvious, which have also been the important step in the history of polymer theories. Additionally, these results might also show that students are not used to evaluating and comparing different theories.

Summary and Conclusions: Design of Educational Materials

This chapter has given reasons and examples for the detailed and comparative analysis of both historical developments of basic concepts and ideas in science and corresponding students' ideas and explanations. The use of historic material to initiate students' thinking and discussions has also been shown by different studies.

In this last part of the chapter we present – as far as possible – a summarising overview about the development of micro–macro thinking in the history of chemistry. Where no investigations concerning students' development of micro-macro-thinking over the time in school were available, we have formulated possible links to historic developments. Further studies, e.g. in the manner of learning process studies would be helpful.

Historical development	Students conceptions/difficulties	Use in classroom
Atomism		
Leukipp (450–360 BC) and Demokrit (460–371 BC) postulate the idea of atoms. They correlate physical properties like hardness and density to the density of packing of atoms.	Many students have a simple atomistic model in mind and are able to make similar micro–macro correlations as the Greece philosophers. Additionally, students bring in new terms like chemical bonding (though not in a chemical sense!)	Leukipp's and Demokrit's ideas seem to be a good start in micro–macro thinking. A deeper insight into their ideas than in the most schoolbooks could pick up students' ideas successfully.
Aristotle (384–322 BC) denies the existence of vacuum, one of the key assumptions in Leukipps and Demokrits model.	Students have difficulties to grasp the idea of empty space between particles (Novick & Nussbaum, 1978; Lee et al., 1993).	Discussing Aristotle's ideas and arguments against them can pick up students conceptions concerning the particulate nature of matter.
Paracelsus (1493–1511) had a more symbolic idea of properties. He treated them as if they were own physical substances.	This kind of non-atomic thinking is also found in 8/9th grade, especially concerning properties like taste, colour or smell (Schlöpke, 1991; Sanmarti, 1995; Steffensky et al., 2005). But students are also able to explain other properties like hardness and melting points with particulate models and cohesive forces (Butts and Smith, 1987).	The idea of substantialisation appears mostly in the case of properties which are extremely difficult to explain. Maybe not all 'metaphors' concerning properties are based on non-atomic thinking.

Historical development	Students conceptions/difficulties	Use in classroom
Inorganic chemistry and ionic bonding		
Renaissance and after: debate about the shape of particles and the correlation to crystal shape. Haüy (1743–1822) and others propose models with edgy particles, whereas Hooke (1635–1703) and many others discuss models with ball-shaped ones.	Both ideas find semblances in students' thinking (Pfundt, 1981; Griffith, 1987).	Both historical theories are easy to grasp for students and can be used to elucidate and discuss students' conceptions in class.
Debate about the question if crystals and solutions consist of single ions or ion pairs.	Taber (1994) and Barke (2006) could show that numerous students misinterpreted the particles of sodium chloride as pairs and not as single ions.	Picking up this debate (as a roleplay etc.) could help, to discuss (and cure) these misunderstandings.
Organic chemistry and covalent bonding		
Liebig (1803–1873) discovered isomerism and concluded the importance of the arrangement of atoms regarding the properties of matter in 1832.	Schmidt (1992) discovered students' difficulties with the concept of isomerism which are not similar to historical ideas.	The importance of isomerism in the history of science does not correspond to the importance of isomerism in school.
Butlerow (1828–1886) relates chemical change to chemical structure and develops the first molecular mechanisms.		Butlerow's analyses are clear and simple examples for chemical structure determination. They could be useful in class to demonstrate the beginning of organic chemistry as science of molecular structures.
Lewis (1875–1946) develops the octet rule and theory of covalent bonding	Some misunderstandings concerning the octet rule are known, which are not related to the historical ideas. (Peterson et al., 1989; Furio et al., 2000)	

Historical development	Students conceptions/difficulties	Use in classroom
Debye (1884–1966) formulates the theory of polar molecules to explain the dielectricity of some substances.	Students have difficulties to determining the shape and polarity of a molecule. (Peterson et al. (1989) resp. Furio et al. (2000))	The connections between students' ideas and scientific conceptions are less tight than above. Especially in the case of intermolecular forces, the contexts that lead to the development of the theory are extremely complex and too complicated for school. Nevertheless, a historical embedding could help students to recognize the focus and the limitations of the theories.
Keesom (1879–1956) used the polarity of molecules to explain the viscosity of substances.		
Based on quantum mechanical calculations, London and Heitler (1904–1981) explain the cohesion of apolar molecules, later called London forces.	Students mix up inter- and intramolecular forces, e.g. to explain the viscosity of substances. (Peterson et al., 1989)	
Huggins (1897–1982) develops the theory of hydrogen bonding.	Students can explain hydrogen bondings correctly, but have difficulties, to predict them from chemical formula and to draw conclusions concerning the physical properties of the substance. (Peterson et al., 1989; Özmen, 2004)	
Macromolecular chemistry		
Mark (1895–1992) and Meyer (1893–1952) suggest that materials like caoutchouk or cellulose are made of small molecules aggregated to micells.	Both theories seem logical to students. They are able to draw conclusion concerning the properties of materials out of the theories.	The importance of scientific debate can be shown. However, the success of the macromolecular theory seems not to be understandable without further material.
Staudinger (1881–1956) develops the theory of polymers.		

The literature analyses have shown similarities between historic concepts and students' pre-concepts. Our own studies again have given interesting hints about the usefulness of historical ideas to enhance students' discussions and reflections of different theories. However, the demand for further information has also become obvious e.g. in the case of the polymer discussion: without any background information about the revolutionary idea of Staudinger, which was in contrast to the general idea of molecules at that time, and without information from modern analytical techniques, the students were not able to distinguish between the two historical ideas. However, this result might lead to the demand of such information in class, too, and could therefore be very fruitful to teach the Nature and History of Science, too, connected with the theories about polymers. The idea of incorporating historical material, as Jansen et al. (1995) and others have suggested, could be fruitful if the demands given in the introductory section of this chapter were taken into consideration: the historic ideas as such can not give the students an idea of how scientific explanations arise and why one theory might be more convincing than another. Only the discussion of the background and the context of investigations and scientific discussions offer an insight into the Nature and History of science and can thereby lead to a better and more convincing understanding about central concepts, such as the one on micro–macro thinking.

Bibliography

In order to generate a bibliography of adequate length, we will only mention the most important historical works next to some historiographical ones. Educational literature is completely indicated.

Butlerow, A. (1861). Einiges über die Structur der Körper [About the Structure of Substances]. *Zeitschrift für Chemie, 4*, 549–560.

Dumas, J. (1840). Über das Gesetz der Substitutionen und die Theorie der Typen [About the Law of Substitutions and the Theory of Types]. *Annalen der Chemie und Pharmacie, 33*(3), 259.

Elias, H.-G. (1985). *Große Moleküle – Plaudereien über synthetische und natürliche Polymere [Big Molecules – Talks about Natural and Synthetic Polymers]*. Heidelberg: Springer.

Errera, J., & Sherrill, M. L. (1929). Dipole moment and molecular constitution. In P. Debye (Ed.), *Dipolmoment und Chemische Struktur [Dipole Moment and Chemical Structure]*. Leipzig: Hirzel.

Estermann, I. (1929). Dipolmoment und Molekülbau [Dipole Moment and the Constitution of Molecules.] In P. Debye (Ed.), *Dipolmoment und chemische Struktur [Dipole Moment and Chemical Structure]*. Leipzig: Hirzel.

Fabian, E. (1986). *Die Entdeckung der Kristalle [The Discovery of Crystals]*. Leipzig: VEB Deutscher Verlag für Grundstoffindustrie.

Farrington, B. (1944). *Greek Science*. Harmondsworth: Penguin Books.

Fierz-David, H. E. (1952). *Die Entwicklungsgeschichte der Chemie [The Development of Chemistry]*. Basel: Birkhäuser.

Frankenheim, M. L. (1835). *Die Lehre von der Cohäsion, umfassend die Elasticität der Gase, die Elasticität und Cohärenz der flüssigen und festen Körper und die Krystallkunde [The Science of Cohesion, including the Elasticity of Gases, the Elasticity and Coherence of Liquid and Solid Bodys]*. Breslau: Schulz.

Geyer, C. (1995). *Die Vorsokratiker [Presocratic Philosophy]*. Hamburg: Junius.

Gloy, K. (1995). *Die Geschichte des wissenschaftlichen Denkens [The History of Scientific Thinking]*. München: Beck

Groth, P. (1979). *Die Entwicklungsgeschichte der mineralogischen Wissenschaften [The History of Mineralogy]*. Wiesbaden: Sändig.

Heitler, W., & London, F. (1927). Wechselwirkung neutraler Atome und homöopolare Bindung nach der Quantenmechanik [Interactions Between Neutral Atoms and Homopolar Bonding According to the Quantum Theory]. *Zeitschrift für Physik, 44*, 455–472.

Hiller, J. F. (1952). Die Mineralogie des Paracelsus [The Mineralogy of Paracelsus]. *Philosophia naturalis, 2*, 293–331.

Hoffman, D. (2006): Peter Debye (1884–1966) – ein typischer Wissenschaftler in untypischer Zeit [Peter Debye (1884–1966) – a Typical Scientist in Untypical Times]. *Preprint des Max Plank Institut für Wissenschaftsgeschichte Nr. 314. Berlin: MPIWG*.

Horne, R. A. (1975). Die Chemie des Aristoteles [Aristoteles' Chemistry]. In G. A. Seeck (Ed.), *Die Naturphilosophie des Aristoteles*. Darmstadt, Wissenschaftliche Buchgesellschaft.

Huggins, M. L. (1936). Hydrogen bridges in organic compounds. *The Journal of Organic Chemistry, 1*(5), 407–456.

Madelung, E. (1909). Molekulare Eigenschwingungen [Molecular Natural Vibration]. *Nachrichten der Gesellschaft für Wissenschaften, 1*, 100–106.

Mansfeld, J. (1986). *Die Vorsokratiker II [Presocratic Philosophy II]*. Stuttgart: Reclam.

Meyer, K. H., & Mark, H. (1928). Über den Bau des kristallisierten Anteils der Cellulose [About the Constitution of the Crystalline Parts of Cellulose]. *Berichte der deutschen chemischen Gesellschaft, 61*, 592–615.

Priesner, C. (1980). *H. Staudinger, H. Mark und K. H. Meyer – Thesen zur Größe und Struktur der Makromoleküle [H. Staudinger, H. Mark and K. H. Meyer – Theories about the Size and Structure of Macromolecules]*. Weinheim: Verlag Chemie.

Seeber, L.-A. (1824). Versuch einer Erklärung des inneren Baus der festen Körper [Attempt to an Explanation of the Inner Constitution of Solid Bodies]. *Gilberts Annalen der Physik, 76*(4), 349–372.

Simon, G. (1980). *Kleine Geschichte der Chemie [A Short History of Chemistry]*. Köln: Aulis und Deubner.

Staudinger, H. (1961). *Arbeitserinnerungen [Memories of my Work]*. Heidelberg: Dr. Alfred Hüthig Verlag.

Stückelberger, A. (1979): *Antike Atomphysik [Ancient Physics of the Atom]*. München: Heimeran.

Van't Hoff, J. H. (1908). *Die Lagerung der Atome im Raume [The Arrangement of Atoms in Space]*. Braunschweig: Vieweg.

Weißbach, H. (1971). *Strukturdenken in der organischen Chemie [Structural Thinking in Organic Chemistry]*. Berlin: VEB Verlag deutscher Wissenschaften.

Literature About Students' Conceptions

Barke, H.-D. (2006). *Chemiedidaktik – Diagnose und Korrektur von Schülervorstellungen [Chemisty Education – Diagnosis and Cure of Students' Conceptions]*. Heidelberg: Springer.

Barker, V. (2004). *Beyond Appearances. Students' misconception about basic chemical ideas. A report prepared for the Royal Society of Chemistry*. Retrieved Oct. 16, 2007 from the World Wide Web: www.chemsoc.org/pdf/learnnet/rsc/miscon.pdf

Bello, S., Herrera, A., & Velázquez, L. (2007). In search of chemistry students' previous ideas related to chemical bonding. *Proceeding of the 2nd European Variety in Chemistry Education*. Praque: Charles University

Ben-Zvi, R., Eylon, B. S., Silberstein, J. (1986). Is an atom of copper malleable? *Journal of Chemical Education, 63*(1), 64–66.

Ben-Zvi, R., Silberstein, J., & Mamlok, R. (1990). Macro-micro relationships. A key to the world of chemistry. In P. L. Lijnse, et al. (Eds.), *Relating macroscopic phenomena to microscopic particles*. Utrecht: CD-Beta Press.

Bigalski, H. (2005): *Entwicklung einer exemplarischen Unterrichtseinheit zur Umsetzung von Bildungsstandards: Vom Kautschuk zum Autoreifen [Development of a exemplary teaching unit for the implementation of National Standards: From Caoutchouk to Wheels]*. Unpublished manuscript, Carl von Ossietzky University, Oldenburg.

Butts, B., & Smith, R. (1987). HSC chemistry students' understanding of the structure and properties of molecular and ionic compounds. *Research in Science Education, 17*, 192–201.

Coll, R. K., & Treagust, D. F. (2003). Learners' mental models of metallic bonding: A cross-age study. *Science Education, 81*, 685–707.

Craft, J., & Miller, J. (2007). Unlocking the atom. *Science Teacher, 74*(2), 24–29.

Donmoyer, R. (2006). Take My Paradigm . . .Please! The Legacy of Kuhn's Construct in Educational Research. *International Journal of Qualitative Studies in Education, 19*(1), 11–34.

Duit, R., & Rhöneck, C. (Eds). (1996). *Lernen in den Naturwissenschaften*. Kiel: IPN.

Garnett, P. J., & Hackling, M. W. (1995). Students' alternative conceptions in chemistry. A review of research and implications for teaching and learning. *Studies in Science Education, 25*, 69–95.

Driver, R., et al. (2000). *Making sense in secondary science*. London: Routledge.

Gault, C. (1991). History of science, individual development and science teaching. *Research in Science Education, 21*, 133–140.

Griffith, A. K. (1992). Grade-12 student's misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*(6), 611–628.

Irwing, A. (1997). Theories of burning. A case study using a historical perspective. *School Science Review, 78*(285), 31–38.

Janes, B. (2004). On the shoulders of giants. *Science Scope, 28*(3), 36–37.

Jansen, W. (1995). Das historisch-problemorientierte Unterrichtsverfahren – ein Forschungsprojekt [The Historical Problem-Centered Conception – A Research Project]. In Günter-Arndt, H., & Raapke, H.-G. (Eds.), *Revision der Lehrerbildung*. Oldenburg: Zentrum für pädagogische Berufspraxis.

Herron, J. D. (1975). High school forum. *Journal of Chemical Education, 52*(2), 179–180.

Höttecke, D. (2004). Wissenschaftsgeschichte im naturwissenschaftlichen Unterricht [The History of Science in Science Education]. In C. Hößle, et al. (Eds.), *Lehren und Lernen über die Natur der Naturwissenschaften* (pp. 43–56). Baltmannsweiler: Schneider.

Kasper, L., Mikelskis, H. F., & Starauschek, E. (2005). Naturwissenschaften im Disput – das Lernmedium Tafelrunde [Science in Debate – Learning with the "Round Table"]. *Naturwissenschaften im Unterricht Physik, 16*(87), 38–40.

Kattmann, U., & Gropengießer, H. (1997). Modellierung der Didaktischen Rekonstruktion [The Model of Educational Reconstruction]. *Zeitschrift für die Didaktik der Naturwissenschaften, 3*(3), 3–18.

Keogh, B., & Naylor, S. (1999). Concept cartoons, teaching and learning in science. *International Journal of Science Education, 21*(4), 431–446.

Kubli, F. (2005). *Mit Geschichten und Erzählungen motivieren [Motivating with Stories and Narratives]*. Köln: Aulis Verlag Deubner.

Kuhn, T.S. (1996). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Lederman, N. (2004). Syntax of nature of science within inquiry and science instruction. In L. Flick& N. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 301–317). Dordrecht: Kluwer Academic Publisher.

Lee, O., Eichinger, D. C., Anderson, D. W., Berkheimer, G. D., & Blakeslee, T. D. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*(3), 249–270.

Lijnse, P., & Licht, P. (1990). Micro-macro. What to discuss? In P. L. Lijnse, et al. (Ed.), *Relating macroscopic phenomena to microscopic particles*. Utrecht: CD-Beta Press.

Marino, S., & Kremer, M. (2002). Auf den Spuren von Georg Ernst Stahl [On the Traces of Georg Ernst Stahl]. *Praxis der Naturwissenschaften – Chemie in der Schule, 51*(1), 8–11.

Mas, C. J., et al. (1987). Parallels between adolescents' conception of gases and the history of chemistry. *Journal of Chemical Education, 64*(7), 616–618.

Masson, S., & Vazquez-Abad, J. (2006). History of science in science education through historical microworlds to promote conceptual change. *Journal of Science Education and Technology, 15*(3–4), 257–268.

Matthews, M. (1992). History, philosophy, and science teaching: The present rapprochement. *Science & Education, 1*, 11–42.

Matthews, M. (2004). Kuhn's impact on science education: What lessons can be learned? *Science & Education, 88*, 90–118.

Matuschek, C., & Jansen, W. (1985). Chemieunterricht und Geschichte der Chemie. [Chemistry Education and the History of Chemistry.] *Praxis der Naturwissenschaften – Chemie, 24*(2), 3–7.

Mayring, P. (2000). *Qualitative Inhaltsanalyse [Qualitative Analysis of Content]*. Weinheim: Beltz PVU.

McKinney, D., & Michalovic, M. (2004). Teaching stories of scientists and their discoveries. *Science Teacher, 71*(9), 46–51.

Minssen, M., & Walgenbach, W. (1985): *Naturstoffe, Kunststoffe und das Makro-molekülkonzept [Natural and Synthetic Polymers and the conception of Macromolecules]*. Kiel: IPN.

Nieswandt, M. (2001). Problems and possibilities for learning in an introductory chemistry course from a conceptual change perspective. *Science Education, 85*(2), 158–179.

Novick, S., & Nussbaum, J. (1978). Junior high school pupils' understanding of the particulate nature of matter. *Science Education, 62*(3), 273–281.

Osborne, R. (1982). Conceptual change – For pupils and teachers. *Research in Science Education, 12*(1), 25–31.

Özmen, H. (2004). Some student misconceptions in chemistry. A literature review of chemical bonding. *Journal of Science Education and Technology, 13*(2), 147–159.

Peterson, R. F., Treagust, D., & Garnett, P. (1989). Development and application of a diagnostic instrument to evaluate grade-11 and grade-12 students' conceptions of covalent bondig and structure following a course of instrucion. *Journal of Research in Science Teaching, 26*(4), 301–314.

Pfundt, H. (1975). Ursprüngliche Erklärungen der Schüler für chemische Vorgänge [Students' Preconceptions of Chemical Processes]. *Der Mathematisch-naturwissenschaftliche Unterricht, 28*(3), 157–162.

Piaget, J. (1971). *Genetic epistemology*. New York: Norton.

Piaget, J., & Garcia, R: (1983). *Psychogenesis and the history of science*. New York: Columbia University Press.

Posner, G., Strike, K., Hewson, P., & Gertzog, W. (1982): Accommodation of a scientific conception: Towards a theory of conceptual change. *Science Education, 66*(2), 211–227.

Pukies, J. (1979). *Das Verstehen der Naturwissenschaften*. Braunschweig: Westermann.

Rudge, D. W., & Howe. E. M. (2004): Incorporating history into the science classroom. *Science Teacher, 71*(9), 52–57.

Sanmarti, N., & Izquierdo, M. (1995). The substantialisation of properties in pupils' thinking and in the history of chemistry. *Science & Education, 4*, 349–369.

Schlöpke, W.-I. (1991). Alchemistisches Denken und Schülervorstellungen über Stoffe und Reaktionen [Alchemist Thinking and Students' Conceptions about Matter and Reactions]. *Chimica Didactica, 17*, 5–43.

Schmidt, H.-J. (1992). *Harte Nüsse im Chemieunterricht [Tough Nuts in Chemistry Classroom]*. Frankfurt a. M.. Diesterweg.

Steffensky, M., Parchmann, I., & Schmidt, S. (2005). "Die Teilchen saugen das Aroma aus dem Tee" – Beispiele und Erklärungsansätze für Missverständnisse zwischen Alltagsvorstellungen und fachlichen Erklärungen. [The Particles are sucking the Aroma out of the Tea. Examples and Explanations for Misunderstanding between Daily Life Conceptions and Scientific Explanations] *Chemie in unserer Zeit, 39*(4), 274–278.

Taber, K. S. (1994). Misunderstanding the ionic bond. *Education in Chemistry, 7*, 100–102.

Van Driel, J. H., De Vos, W., & Verloop, N. (1998). Relating students' reasoning to the history of science. The case of chemical equilibrium. *Research in Science Education, 28*(2), 187–198.

Vosniadou, S., & Brewer, W. F. (1987). Theories of knowledge restructuring in development. *Review of Educational Research, 57*(1), 51–67.

Wandersee, J. H., & Griffard, P. B. (2003). The history of chemistry. Potential and actual contributions to chemical education. In J. K. Gilbert, et al. (Eds.), *Chemical education. Towards research based practice* (pp. 29–46). Dordrecht: Kluwer Academic Publishers.

Wehlen, C. (2006). *Erkenntnisgewinnung am Beispiel der Kunststoffe – Analyse wissenschaftlicher Vorstellungen und populärwissenschaftlicher Darstellungen [The Gain of Knowledge at the Example of Plastics – Analysis of scietific ideas and Popular Science Representations]*. Unpublished manuscript, Carl von Ossietzky University, Oldenburg.

Chapter 11
The Roles of Multimedia in the Teaching and Learning of the Triplet Relationship in Chemistry

Mei-Hung Chiu and Hsin-Kai Wu

Abstract Ever since Johnstone (1993) addressed the three levels of chemistry (symbolic, macro, and microscopic or so called submicro currently), many studies investigate how multimedia could support constructing, developing, and evaluating students' mental representations of chemistry at the three levels. This chapter focuses on how multimedia could enhance chemistry learning of the triplet relationship and discusses theories and empirical studies from the following perspectives: (1) multimedia as a modeling tool (discussing multiple representations and mental models in learning and teaching chemistry), (2) multimedia as a learning tool (introducing tools such as 4M:Chem, eChem, and ChemSence), (3) multimedia as an assessment tool (such as presenting computerized two-tier diagnostic instruments), and (4) multimedia as an instructional tool (linking findings of students' mental representations to the development of teachers' pedagogical content knowledge in chemistry). Implications for chemical education are discussed in terms of theoretical and practical approaches.

Introduction

Ever since Johnstone (1993) addressed the three levels of chemistry (symbolic, macro, and microscopic, called submicro currently), many studies have investigated how multimedia could support the construction, development, and evaluation of students' mental representations of chemistry at the three levels. The studies in the previous chapters mention that the representations of the macro–submicro–symbolic relationship play important roles in chemical concept learning.

This chapter draws attention to the role of multimedia in learning, teaching, and assessing chemical education. In particular, this chapter focuses on how multimedia can enhance chemistry learning of the relationship between the symbolic, macro, submicro levels of chemistry and discusses theories and empirical studies from the following perspectives: (1) multimedia as a representational modeling tool

---

M.-H. Chiu (✉)
National Taiwan Normal University, Taiwan, Republic of China
e-mail: mhchiu@ntnu.edu.tw

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_12,

(discussing multiple representations and mental models in learning and teaching chemistry), (2) multimedia as a learning tool (introducing tools such as 4M:Chem, ChemSense, Molecular Workbench, and Connected Chemistry), (3) multimedia as an assessment tool (for example, presenting computerized two-tier diagnostic instruments), and (4) multimedia as an instructional tool (linking findings of students' mental representations to the development of teachers' pedagogical content knowledge in chemistry). It concludes with a discussion of the implications for chemical education, which are considered in terms of theoretical and practical approaches.

Multimedia as a Modeling Tool

Representations are ways to express phenomena, objects, events, abstract concepts, ideas, processes, mechanisms, and even systems. They have various or alternative purposes to *re*-present the real, hypothetical, or imaginative entity, regardless of its nature. Along with the different purposes of representations are different formats for depicting an entity. For instance, ethanol can be expressed as C_2H_5OH to show its nature, C_2H_6O to show its components, or its structure. However, things become more complex when we investigate the molecular structures in 3D to form an internal representation and then manipulate it mentally (such as deciding C_2H_5OH is an organic compound, stereo-isomers). In addition, the nature of scientific concepts per se (having a dynamic, abstract, complicated, and nonobservable nature) makes learning chemistry conceptually difficult (Wandersee, Mintzes, & Novak, 1994).

Craik (1943), the pioneer of mental models, depicts a mental model as a kind of dynamic representation or simulation of the world from which one can make inferences, generate actions, or relate symbols to the world. Johnson-Laird (1983, p. 470) commented that a primary source of mental representations is perception. Internal representations may encode relatively superficial features of the world. Human's phenomenological experience of the world is a result of natural selection. The vast range of mental models must be constructed by finite means—using primitive symbols and the basic processes that operate on the symbols. Vosniadou and Brewer (1992) consider that mental models are dynamic structures that are formed while answering questions or solving problems or when confronted by some situation. Gilbert, Boutler, and Elmer (2000) point out that the construction of mental models and the presentation of expressed models of scientific phenomena are central to understanding any phenomenon or body of information. Grosslight, Unger, and Jay (1991) state that students need more experience using models as intellectual tools and more time to reflect on the experience.

In science classrooms, it is essential to emphasize the role and purpose of scientific models and then provide examples of or opportunities to construct model-based cognitive tools for learning science (Treagust, Chittleborough, & Mamiala, 2002). Buckley and Boulter (2000) propose a framework that explains the interactive nature of the relationships among expressed models, mental models, and phenomena. In this way, the purpose of modeling and models in science education can be categorized and regarded as helping with understanding scientific contents, thinking logically and creatively, constructing a knowledge structure, communicating, cultivating problem-solving skills, and making evaluations in the course of scientific learning.

Going one step further with the interactive nature of mental models, modeling and models should be capable of forming a bridge between science education and technology in many ways (Gilbert et al., 2000). Hennessy, Deaney, and Ruthven (2006) advocate that multimedia simulation is considered one of the most powerful applications of information and communication technologies to science at present. Simulations are perceived to add value to learning activities, overcoming some of the constraints of regular classes. Gilbert (2007) claims that visualization, via multimedia, incorporates mental imagery, which is produced in the process of perceiving an object that is seen or touched, into a phenomenon. Model-based teaching and learning facilitate the construction of mental models through a recursive process of formation, use, version, and elaboration (Buckley, 1995; Buckley and Boulter, 2000). Therefore, multimedia is one of the tools that is considered to be effective in learning scientific concepts.

A study (Chan, 2002) conducted in the first author's research lab shows how one under discussion in this paper was designed to elaborate on the role of multimedia and multiple representations in learning scientific concepts and to investigate the effectiveness of dynamic representations on students' learning. Chan (2002) developed a computer-based set of dynamic analogies. The research investigated 53 eighth graders who were learning chemical equilibrium. The students were randomly assigned to three groups: control group (C); analogy and instruction group (A); and analogy, instruction, and animation with dynamic analogy group (D). Six target students were chosen from each group to be interviewed for their conceptual change via learning with model-based animation and dynamic analogy instruction. The design of the experiment is shown below (Fig. 11.1).

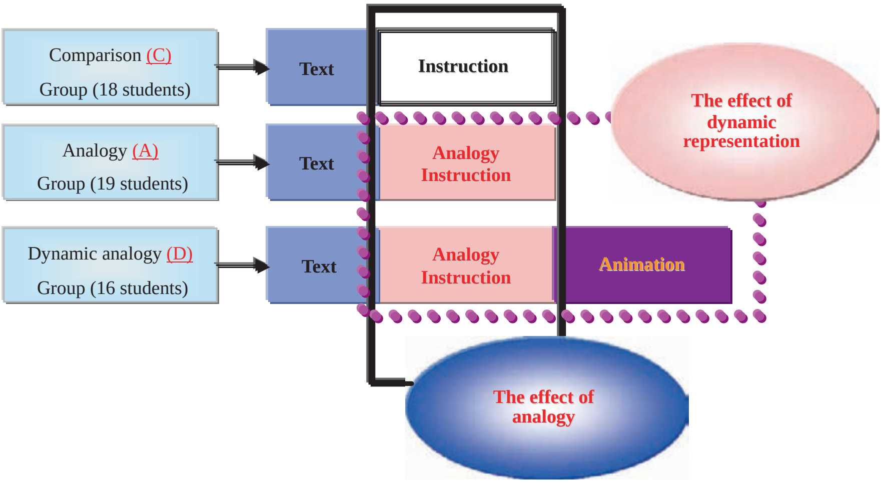


Fig. 11.1 The design of the experiment (Chan, 2002)

The target concept to be learned in the study was chemical equilibrium. The context is adding SCN^- into Fe^{3+} solution to show how the color changes over a period of time. The analogy used in the simulation was a ballroom containing some boys and then inviting girls to the stage. Over a period of time, there are a constant number of boys and girls. Which person is on the stage might be different over time but the platform keeps a maximum number of persons on the stage. In this analogy, it is implied that the girls represent the Fe^{3+} and the boys represent the SCN^- particles. At saturation situation point, the total amount of ions (Fe^{3+}, SCN^-, and $FeSCN^{2+}$) of the solution was kept the same. The students saw the animated dancing couples as well as observed how the analogy was matched with the representation of a chemical reaction, as shown in Fig. 11.2.

The results show that the students' performance in the three groups was not significantly different at the pretest (Fig. 11.3). However, the posttest revealed both analogy group A and dynamic analogy group D outperformed the control group C and that D group performed better than A group on the gained scores. The two groups did better than the control group on the posttest as well as on on the retaining test. Between analogy group A and dynamic analogy group D, there were significant differences on the pretest and the posttest.

From the qualitative analysis, Chan found that students' mental models could be categorized into three types: initial, synthetic, and scientific mental models (Fig. 11.4). The initial model refers to the static model, which had only solute dissolved into the solution and then stopped at the saturation point. The synthetic model refers to the coexistence of two models: the unidirectional model and

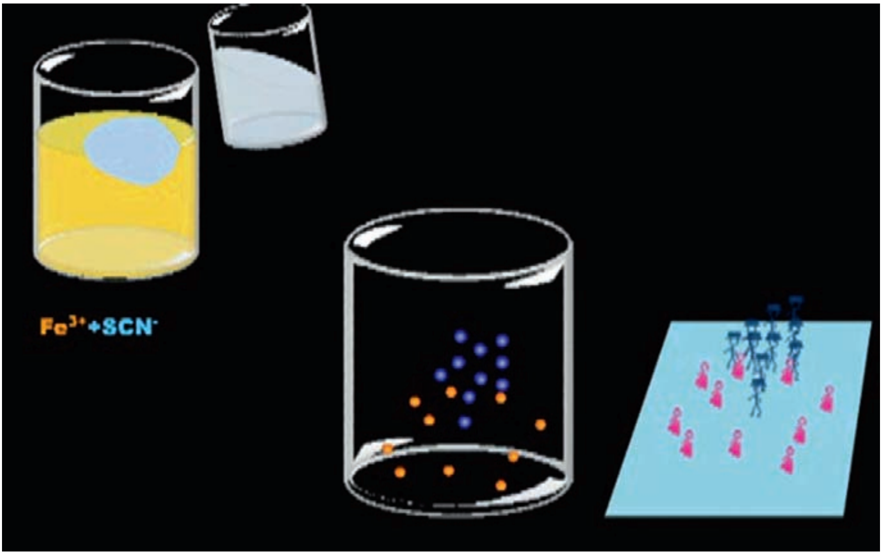
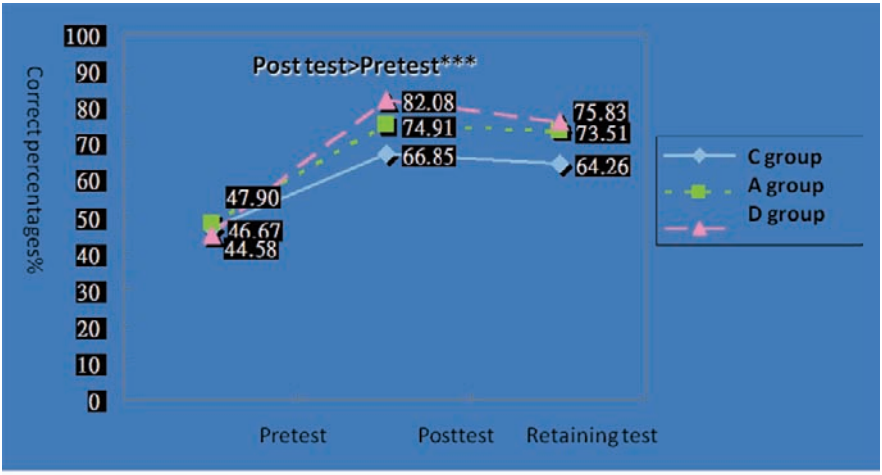


Fig. 11.2 The analogy representation in the study



*p < .1 ; **p < .05 ; ***p < .001

Fig. 11.3 The quantitative result of the study

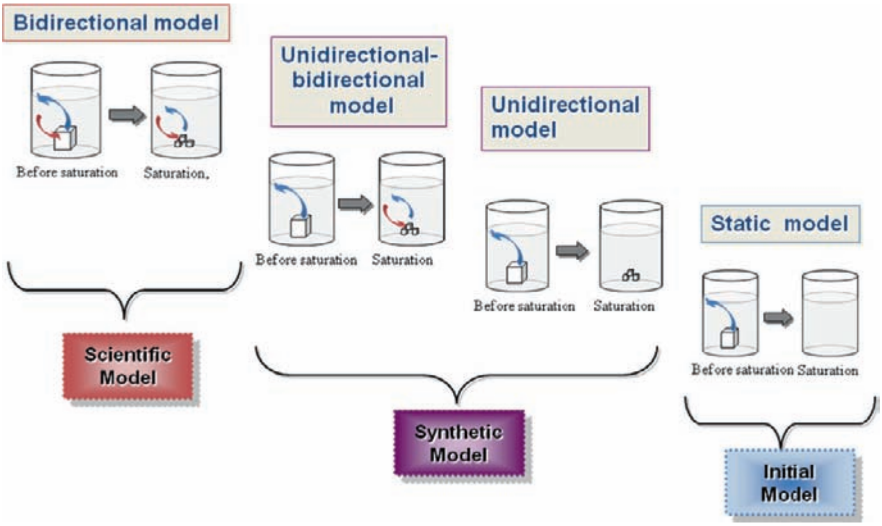


Fig. 11.4 The qualitative analyses of the students' mental models of chemical equilibrium

the unidirectional–bidirectional model. Finally, the scientific model refers to the bi-directional movement of the particles model before and at the saturation situation point. From the analysis, we found that the students benefited from the multiple representations activities that helped them construct correct mental models via the simulation activities presented to them.

Summary

The difficulty of learning science can be attributed to the nature of scientific concepts, which are complex and unobservable. The use of multimedia—dynamic, simulated, or analogical representations that depict the essence of the concepts in an attempt to match the scientific concepts with expressed or external models to help learners develop concepts or ideas about phenomenon—could play a role in explaining phenomena. It helps the imagination extend a repertoire of abstract knowledge that makes science meaningful to learners. In the example discussed above, we found that the students connected chains of the multiple representations of chemical equilibrium and a mix of their personal conceptions and analogies. The involvement of the multiple representations from personal experiences with the submicroscopic interactions among particles suggests that the dynamic analogies used in this study provide a channel for students to construct a model to be manipulated while expanding their conceptual repertoire of chemical equilibrium. In addition, we also found that not only did the multimedia allows the learners to see each individual particle motion but it also displays a collective motion of particles. This is an essential nature of particle motion. This also implies that students need even more opportunities and active scaffolding to make connections between their experiences and formal science concepts introduced at school.

Multimedia as a Learning Tool

This section focuses on how multimedia tools could support students' learning of the triplet symbolic–macro–submicro relationship. It has been well documented that students at the secondary school level have difficulty comprehending and translating submicro and symbolic representations (Keig & Rubba, 1993). Most of them are unable to represent chemical concepts at the submicro and symbolic levels (Krajcik, 1991), to visualize the interactive and dynamic nature of chemical process by viewing symbols and equations (Ben-Zvi, Eylon, & Silberstein, 1988), and to form three-dimensional (3D) images by visualizing two-dimensional (2D) structures (Tuckey, Selvaratnam, & Bradley, 1991). To ease students' difficulties, various multimedia tools have been designed to help students visualize imperceptible chemical entities (e.g., atoms and molecules) represented by chemical symbols and to develop their understanding of the triplet relationship (Ardac & Akaygun, 2004; Ealy, 2004; Pallant and Tinker, 2004; Stieff and Wilensky, 2003; Wu, Krajcik, & Soloway, 2001).

In this section, multimedia tools refer to computer-based systems that integrate multiple symbol systems (Salomon, 1979), such as text, audio, video, graph, and animation, to demonstrate chemical entities and/or processes at the macro, submicro, or symbolic levels. In the following, we review four multimedia tools—4M: Chem, ChemSense, Molecular Workbench, and Connected Chemistry—and use the design principles suggested by Wu and Shah (2004) to summarize how these tools support students in learning chemistry.

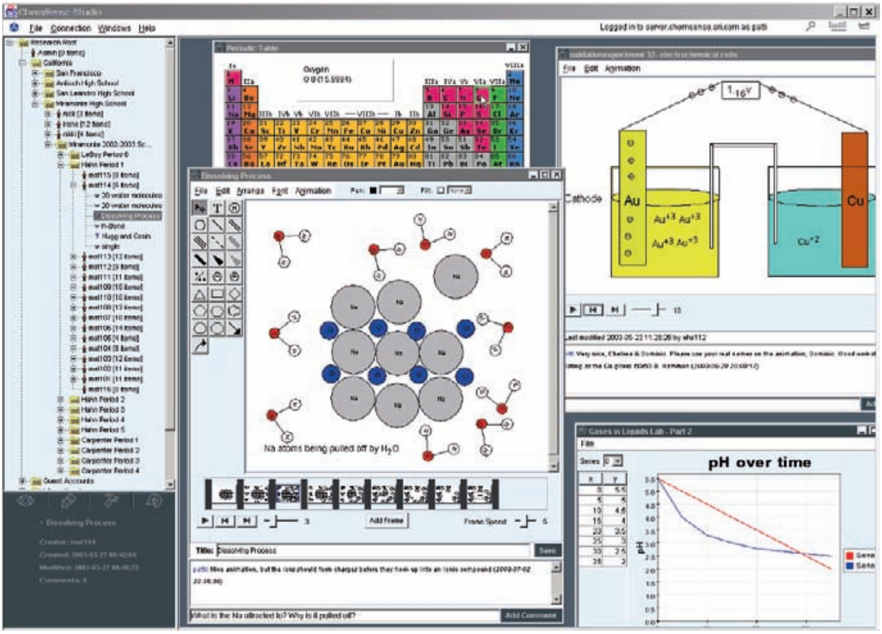
4M:Chem

MultiMedia and Mental Models (4M:Chem) developed by Kozma and Russell (Kozma & Russell, 1997; Kozma, Russell, Jones, Marx, & Davis, 1996) was designed to help students recognize relationships among chemical entities at different levels and comprehend representations by underlying concepts instead of surface features. For example, to present a chemical equilibrium process, $2NO_2$(g) (brown)↔ N_2O_4(g) (colorless), 4M:Chem uses a fourfold divided screen that displays a video segment showing the change of color within a enclosed tube under different temperatures, an equation with chemical formulas and symbols, an animation showing the interaction and movement of molecules at the microscopic level, and a graph showing how the concentrations of two gases changed over time. These four representations are shown simultaneously and linked to each other. A newer version of 4M:Chem, SMV:Chem (Synchronized Multiple Visualization of Chemistry), is distributed by John & Wiley.

When using 4M:Chem, students are encouraged to identify the referential links among the four representations. Kozma (2000) found that to make sense of these representations, students engaged in thoughtful discussions about concepts and established relationships among the macro, submicro, and symbolic levels. Additionally, this multimedia tool encourages students to construct a dynamic model of chemical processes, and their understanding of a phenomenon is shaped by the unique characteristics of a symbol system (Kozma, 2000; Salomon, 1979). For example, the animation-only group performed significantly better than the graph-only group on test items that involved the dynamic nature of chemical equilibrium. However, Kozma (2000) also showed that the group receiving all three media and the video-only group did not score significantly higher than the other groups. Processing multiple representations simultaneously may be highly demanding of cognitive resources (Cook, 2006). Reducing cognitive load by making visual and verbal information explicit and integrated is particularly critical for students who have low visualization skills (Wu and Shah, 2004).

ChemSense

To provide students with opportunities to practice various representational skills (e.g., translating and interpreting chemical representations) and help them represent chemical concepts at the submicro level, ChemSense (http://chemsense.org/), developed by SRI International, integrates features of modeling and multimedia tools (Fig. 11.5). This learning environment offers a set of tools such as a notepad, a spreadsheet, a graphing tool, and an animation tool (animator) to support students' hands-on investigations with Probeware (Novak & Gleason, 2000). Different from 4M:Chem, in which the videos, graphs, and animations are prebuilt and students cannot alter and create visual representations to meet their learning needs, ChemSense allows students to construct models, collect data, make graphs, and



Title: Dissolving Process

What is the Na attracted to? Why is it pulled off?

Fig. 11.5 The ChemSense environment contains a set of tools

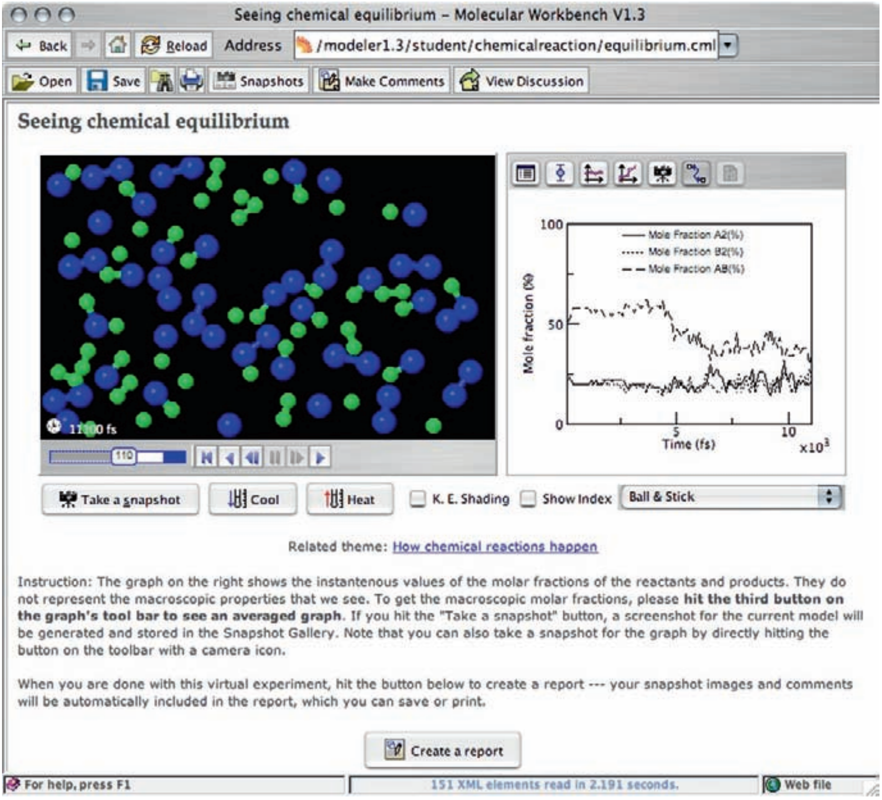
create animations (Schank and Kozma, 2002). Through generating models and illustrations of their understanding about submicro scale interactions, students focus their attention on molecular motions and move back and forth among the three levels. Additionally, while students can use most multimedia tools only individually, ChemSense provides a sharing tool that encourages students to construct representations collaboratively in a social context and to review each other's work by way of commentary.

Schank and Kozma (2002) found that with ChemSense, high school students demonstrated more representational skills such as creating drawings and using animations to externalize their thinking. They also developed a deeper understanding of the structure of a molecule and the interactive aspect of a chemical reaction. Additionally, through creating animations and models on ChemSense, students seemed more focused on the dynamic process of a chemical reaction and demonstrated significantly better performance when representing scientific phenomena at the submicro level (Schank and Kozma, 2002).

Molecular Workbench

Molecular Workbench (MW) is a two-dimensional molecular dynamics application written in Java and created by Concord Consortium (http://workbench.concord.org/). It provides multiple representations and molecular dynamic simulations that allow students to manipulate parameters, such as atomic/molecular mass, position, diameter, attractive force, and initial velocity of particles. Additionally, while the tools and interfaces embedded in 4M:Chem and ChemSense cannot be changed by teachers, MW provides teachers and curriculum developers with an easy-to-use authoring tool for designing user interfaces, creating guided activities, and revising and expanding the existing topics and learning activities on MW. This authoring capability that provides flexibility for teachers to create new simulations and activities can be viewed as an important characteristic of the second generation of multimedia and computer-based tools, which can also be seen in the TELS learning environment (http://www.telscenter.org/) and Connected Chemistry.

With MW, students can interact with the interface (Fig. 11.6) and visualize what happens to collections of interacting atoms and molecules under different conditions and rules (Xie & Tinker, 2006). MW can also help increase students' understanding of submicro scale phenomena through developing more scientifically accurate mental models of atoms and molecules (Pallant and Tinker, 2004). These models, in turn, could support students to effectively predict or explain chemical phenomena at different representational levels.



Seeing chemical equilibrium

Related theme: How chemical reactions happen

Instruction: The graph on the right shows the instantenous values of the molar fractions of the reactants and products. They do not represent the macroscopic properties that we see. To get the macroscopic molar fractions, please **hit the third button on the graph's tool bar to see an averaged graph**. If you hit the "Take a snapshot" button, a screenshot for the current model will be generated and stored in the Snapshot Gallery. Note that you can also take a snapshot for the graph by directly hitting the button on the toolbar with a camera icon.

When you are done with this virtual experiment, hit the button below to create a report --- your snapshot images and comments will be automatically included in the report, which you can save or print.

Fig. 11.6 Molecular Workbench simulation of chemical equilibrium

In their initial studies, Pallant and Tinker (2004) found that after learning with the molecular dynamic models, 8th and 11th grade students were able to relate the difference in the state of matter to the motion and the arrangement of particles. They also used atomic or molecular interactions to describe or explain what they observed at the macroscopic level. Additionally, students' interview responses included fewer misconceptions, and they were able to transfer their understanding of phases of matter to new contexts. Therefore, Pallant and Tinker (2004) concluded that MW and its guided exploration activities could help students develop robust mental models of the states of matter and reason about atomic and molecular interactions at the submicro level.

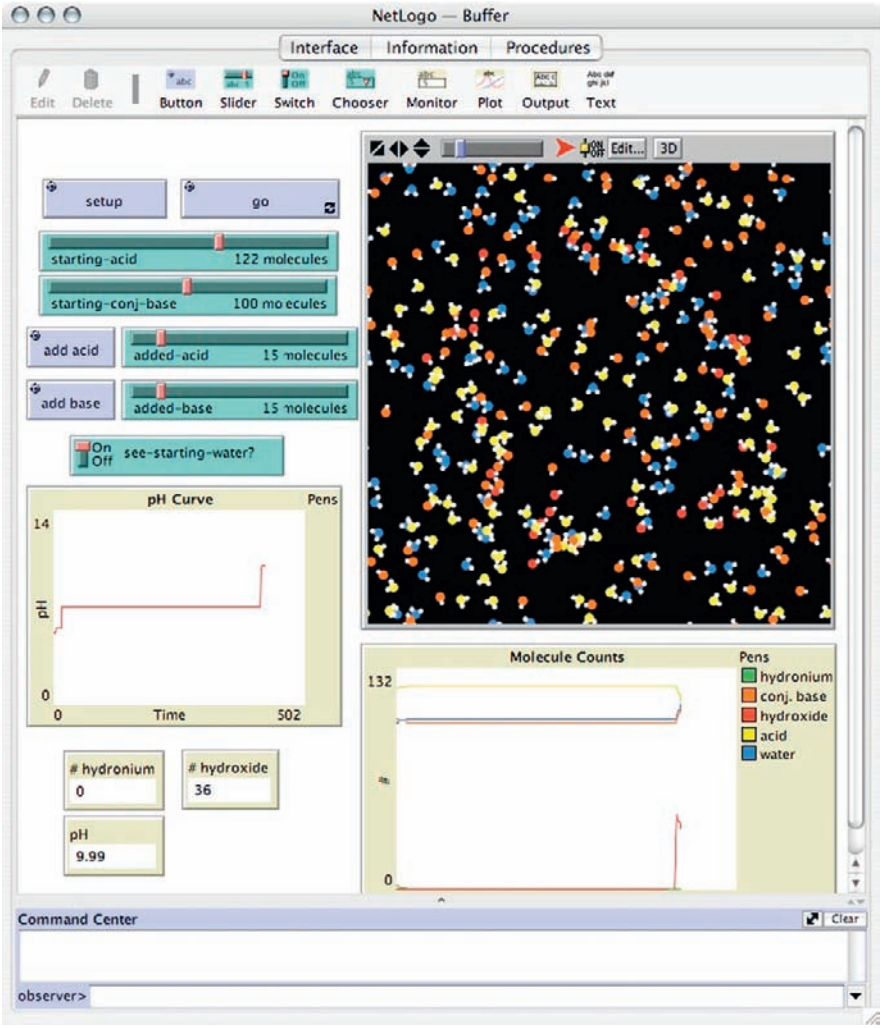
Connected Chemistry

Connected Chemistry (CC) is a modeling and simulation package implemented inside the NetLogo modeling environment (http://ccl.northwestern.edu/netlogo/ models/). Similar to Molecular Workbench, CC is created to present how a macroscopic event in chemistry results from molecular interactions at the submicro level. It allows students to explicitly observe the connections between the submicro, macro, and symbolic levels of chemistry and to explore the interactions by setting various parameters such as concentration, Ka/Kb value, temperature, and number of particles (Fig. 11.7). Taking a "glass box" approach (Wilensky, 1999), CC allows students not only to explore the behavior of prebuilt simulations designed to focus on some target concepts, but also to test and change the underlying rules that control the individual elements of a simulation. With CC, students can add and remove variables from the interface window, alter the NetLogo programming code to change the molecular behavior, and have "virtually unlimited opportunities to interact with and to manipulate a simulated molecular world to gain a deeper understanding of core chemistry concepts and phenomena" (Stieff and Wilensky, 2003, p. 285).

In Stieff and Wilensky (2003), six college students majoring in science were interviewed regarding concepts of chemical equilibrium. The study showed that during the interview, with the use of CC simulations, students demonstrated a dramatic change in conceptions, articulation, and problem solving. Their understanding of the dynamic nature of chemical equilibrium improved and they were able to explicitly link multiple representations and levels in order to gain a deeper understanding when using Connected Chemistry.

Summary

Based on a comprehensive review of chemistry education literature, Wu and Shah (2004) suggest five principles for designing multimedia tools that help students understand concepts and develop their representational skills (e.g., making translations among representations, creating representations to externalize thinking, and



starting-acid 122 molecules

starting-conj-base 100 molecules

added-acid 15 molecules

added-base 15 molecules

On Off see-starting-water?

hydronium 0

hydroxide 36

pH 9.99

Fig. 11.7 Connected Chemistry simulation of a buffer solution

visualizing the interactive and dynamic nature of chemical reactions): (1) provide multiple representations and descriptions, (2) make linked referential connections visible, (3) present the dynamic and interactive nature of chemistry, (4) promote the transformation between 2D and 3D, and (5) reduce cognitive load by making information explicit and integrating information for students.

All of the four multimedia tools reviewed in this section have features to support the first three principles; all of them include multiple and linked representations at the macro, submicro, and symbolic levels, such as texts, graphs, chemical symbols, animations, and videos. Not only do they present the dynamic and interactive nature of chemical phenomena, but they also allow students to explore and manipulate various parameters and to answer “what if” questions. The empirical studies also showed that all the tools can support students in understanding the triplet relationship through interactions with the tools. Yet, only Connected Chemistry offers a 3D view to promote the transformation between 2D and 3D representations, and not all tools address the issue of cognitive load. As the use of multimedia tools increases, students with limited spatial ability may be disadvantaged in learning chemistry, especially if the multimedia tools add another burden to their cognitive capabilities (Cook, 2006).

Multimedia as an Assessment Tool

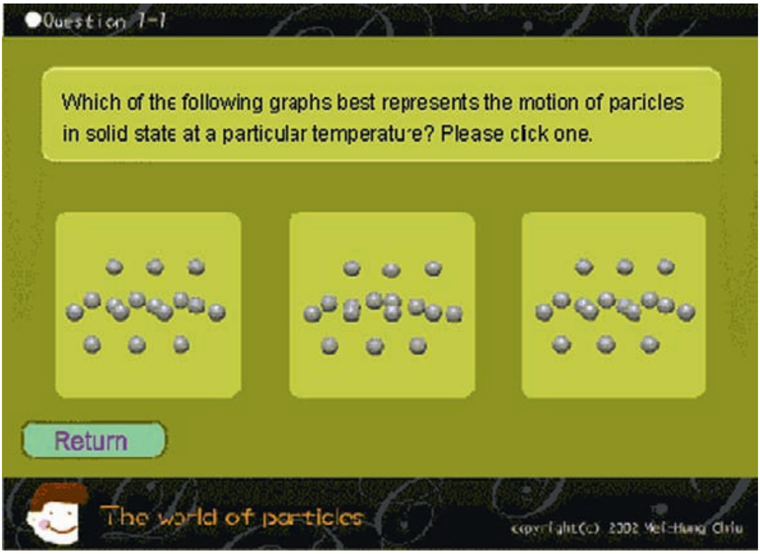
Learning is a complex cognitive activity, where the construction of knowledge requires integrating information from past experiences with the current context and instruction. In order for assessments to provide valid and reliable information for improving the teaching of science, the creators of multimedia tools must align learning trajectories with teaching. The increase in the use of information and communication technologies (ICT) allows educators to change their assessments of learning from those that are based on a traditional approach to ones based on an innovative approach.

Most of the cases we have looked at involve the use of multimedia for teaching and learning purposes. This section introduces two cases that use a similar format: a two-tier multiple-choice diagnostic instrument with multimedia to investigate the characteristics of students’ conceptions about matter and particles. It also looks at the reasons for their responses to a particular problem.

Case 1

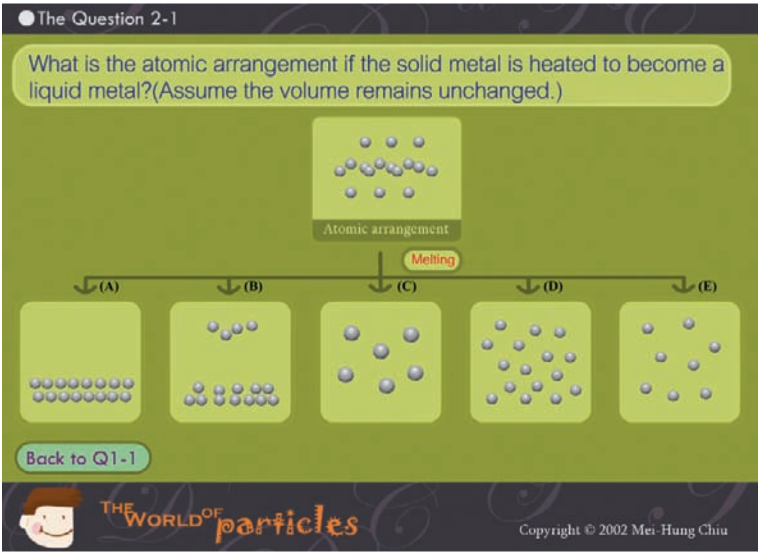
Chiu, Chiu, and Ho (2003) employed a two-tier testing technique proposed by Treagust (1988, 1995), extending this approach to a computerized simulation to obtain the knowledge structure of solid, liquid, and gas held by 39 10th graders (15–16-year-olds). The study involved two parts: first, they conducted open-ended and several semi-structured interviews. This part also involved drawing and the use of Styrofoam, followed by a paper-and-pencil test covering the arrangements and behaviors of particles in three states (solid, liquid, and gas). They gathered 40 students’ explanations for each open-ended question in order to develop multiple-choice test items based on the learners’ understanding of chemistry.

Second, using the results from the first stage, they designed a software program with dynamic representations (each choice was analyzed from the students’ verbal or written explanations) to help them investigate what representative knowledge the learners had of chemistry concepts and how they explained the concepts. For instance, three types of students’ conceptions about the motion of particles in solid state were found as shown in Fig. 11.8. To show the dynamic movements and



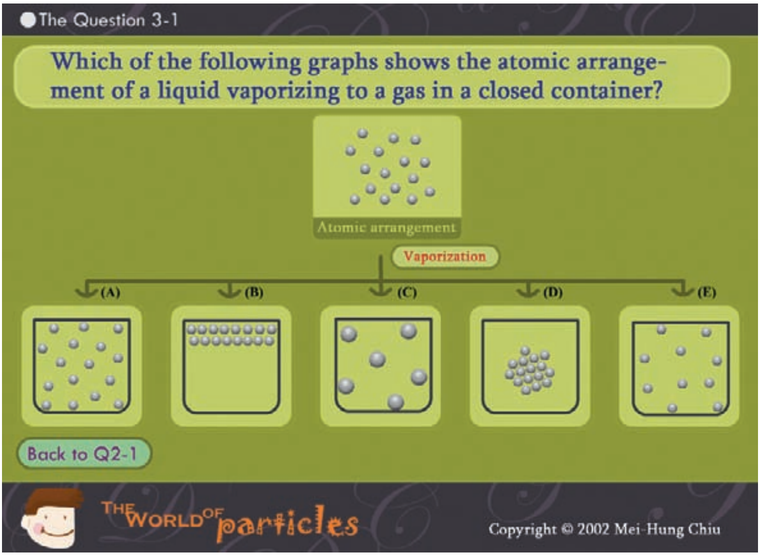
Which of the following graphs best represents the motion of paricles in solid state at a particular temperature? Please click one.

Fig. 11.8 Question 1-1 in the test
Note: Although these three pictorial representations look exactly the same, the particles actually acted differently in still motion than when vibrating.



What is the atomic arrangement if the solid metal is heated to become a liquid metal?(Assume the volume remains unchanged.)

Fig. 11.9 Question 2-1 in the test



The Question 3-1

Which of the following graphs shows the atomic arrangement of a liquid vaporizing to a gas in a closed container?

Fig. 11.10 Question 3-1 in the test

structures of particles, they used FLASH, a computer application tool, to present particles' motions in the three states. The students, who did not learn the concepts and never saw these types of dynamic test items before, were tested individually in a computer lab. In total, there were 12 test items validated by the chemists. Three sets of questions were designed as shown in Figs. 11.8, 11.9, and 11.10. Each set of questions focused on factual knowledge first and then prompted for the reason for the chosen item.

Set 1:
(1-1-1) Which of the following graphs best represents the motion of particles in solid state at a particular temperature? Please click one.
(1-1-2) The one you have chosen is shown below. Please explain your answer.
(1-2) Is there anything between the atoms? Why?
(1-3) If there is another solid metal that consists of the same materials at the same temperature, would the atoms be arranged in the same way? Why or why not?
Set 2:
(2-1-1) Which of the following graphs shows the atomic arrangement of a solid melting to form a liquid (assuming that the volume remains constant)? Why?
(2-1-2) Your choice is shown below. Please explain your answer.
(2-2-1) Which of the following graphs best represents the movement of particles in a liquid?
(2-2-2) Your choice is shown below. Please explain your answer.
Set 3:
(3-1-1) Which of the following graphs shows the atomic arrangement of a liquid vaporizing to form a gas in a closed container?

(3-1-2) Your choice is shown below. Please explain your answer.
(3-2-1) Which of the following graphs best represents the movement of particles in a gas?
(3-2-2) Your choice is shown below. Please explain your answer.

The main findings were,

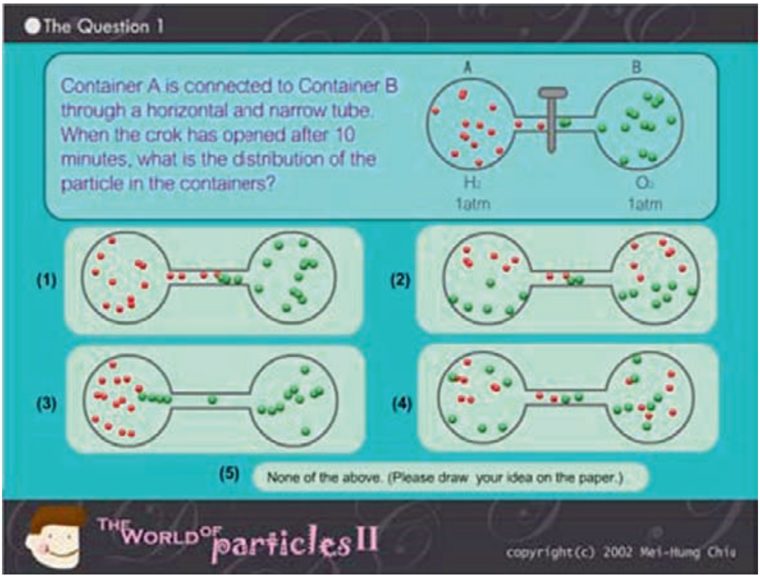
(1) The majority of students were able to provide correct answers to their choices about the atomic arrangement of solid and liquid.
(2) Six students thought that the particles stayed still at the solid state and 13 students thought that there was no space between the atoms. This result is consistent with Griffith & Preston (1992) study.
(3) Six students claimed that the attractive force decreases to allow the particles to fill in the entire container.
(4) Few students believed that the size of the particles increases when the temperature increases.
(5) Some students thought that atoms sink to the bottom of a container (choice A) when something changes from the solid to the liquid state, or some float on the surface (choice B).
(6) The students who chose the same figure that best represented their conception of particulates in gas often offered different explanations for their choices.

With the design of a two-tier test format, we served three purposes: First, we interviewed the students to obtain their explanations of the phenomena that were presented to them in a dynamic representational form. Second, we were able to transform their explanations into graphical representations in order to conduct a relatively large sample size of students. Third, the outcomes of their performance on the diagnostic items revealed their internal representation of knowledge about particles in three states. More importantly, we were able to make inferences about how the students linked their understanding of a macroscopic phenomenon in a context to a microscopic representation that they could hardly grasp using a traditional assessment instrument.

Based on this experience, a computerized program was further developed on related topics to examine how students solved problems in particle distribution with a different orientation of the apparatus and pressures of gas particles. Case 2 below states the major design and findings of this follow-up study.

Case 2

Liang and Chiu (2003) investigated what junior high (8th and 9th) students' mental models were when they confronted distribution problems with different amounts of pressure of gases and a different orientation of the apparatus. Participating in this study were 102 9th graders and 93 8th graders in Taipei. They were normally distributed into classes based on their academic ability. Each student was allotted one computer and 25 minutes for completing the test work. Six test items were

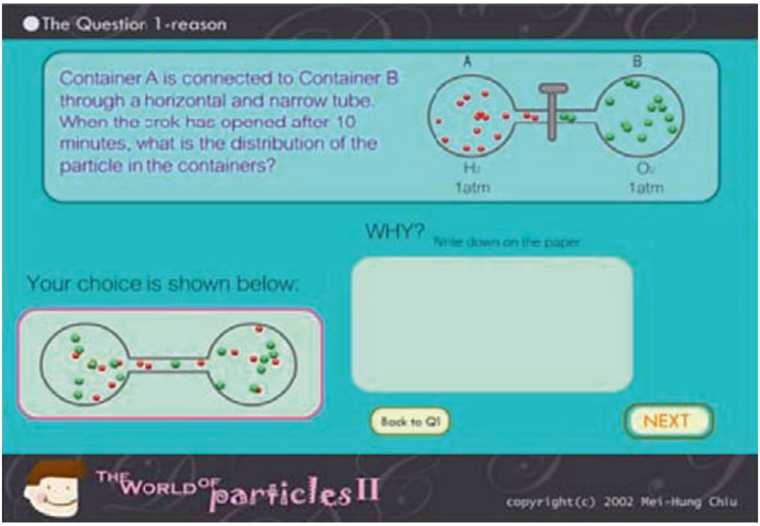


The Question 1

Container A is connected to Container B through a horizontal and narrow tube. When the crok has opened after 10 minutes, what is the distribution of the particle in the containers?

(5) None of the above. (Please draw your idea on the paper.)

Fig. 11.11 The first tier of Question 1



The Question 1-reason

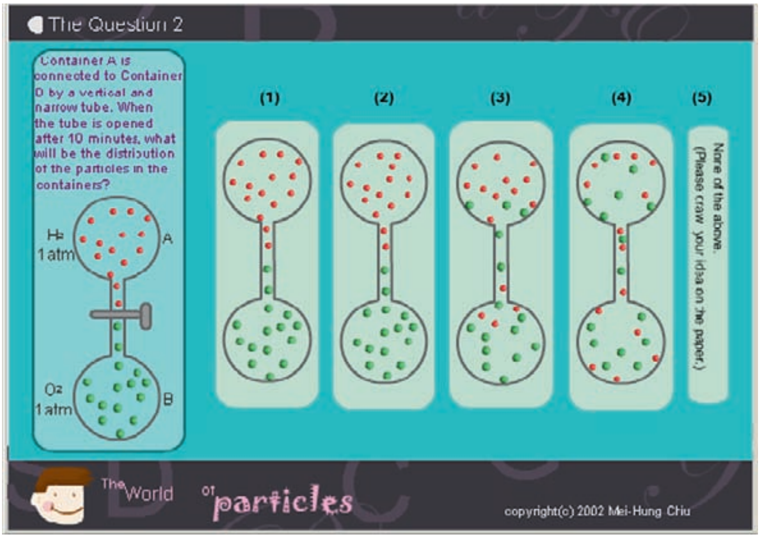
Container A is connected to Container B through a horizontal and narrow tube. When the crok has opened after 10 minutes, what is the distribution of the particle in the containers?

WHY? Write down on the paper

Your choice is shown below:

Fig. 11.12 The second tier of Question 1

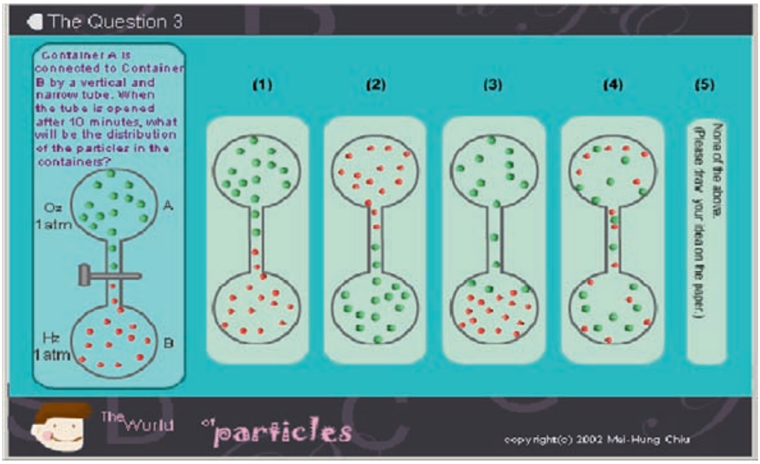
developed and categorized into two sets based on the horizontal and vertical configuration of the apparatus (Figs. 11.11, 11.12, 11.13, 11.14, 11.15, 11.16, and 11.17). Students were asked to decide what would happen to the gases when the faucet connecting the two round containers was open and to provide the reasons for their choices.


The Question 2

Container A is connected to Container B by a vertical and narrow tube. When the tube is opened after 10 minutes, what will be the distribution of the particles in the containers?

None of the above. (Please draw your idea on the paper.)

Fig. 11.13 The first tier of Question 2

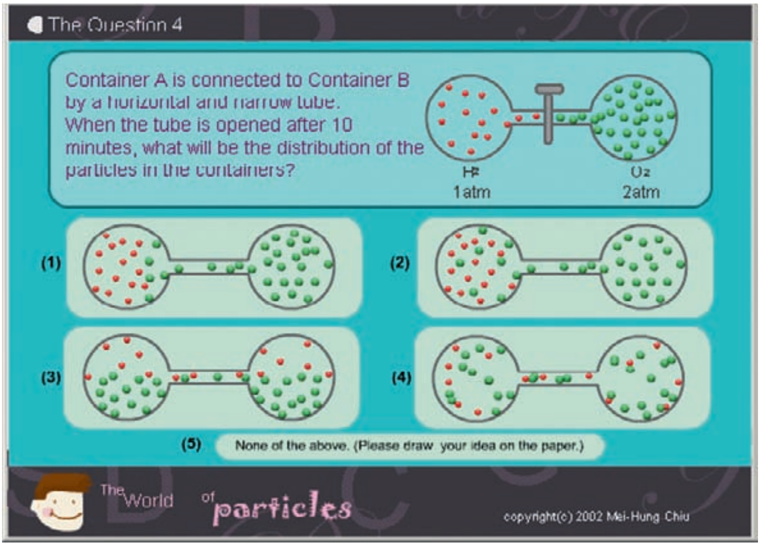

The Question 3

Container A is connected to Container B by a vertical and narrow tube. When the tube is opened after 10 minutes, what will be the distribution of the particles in the containers?

None of the above. (Please draw your idea on the paper.)

Fig. 11.14 The first tier of Question 3

The results revealed that only 26% of the ninth grade students answered all six questions correctly, whereas 20% of eighth graders answered all six questions correctly (Table 11.1). On average, the students performed better when the amount of gas pressure, regardless of whether the apparatus was set horizontally or vertically, was equal to the gases at different pressure situations. Concerning the effect of orientation of the apparatus, the result did not show salient differences in eighth and ninth grade students.

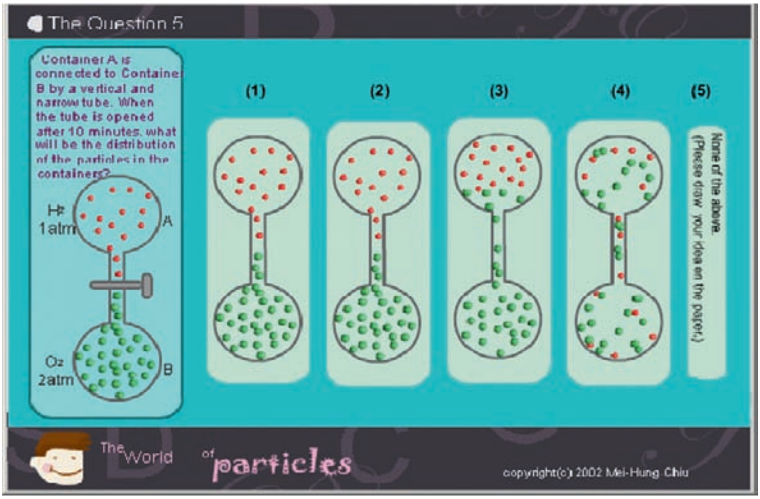


The Question 4

Container A is connected to Container B by a horizontal and narrow tube. When the tube is opened after 10 minutes, what will be the distribution of the particles in the containers?

(5) None of the above. (Please draw your idea on the paper.)

Fig. 11.15 The first tier of Question 4

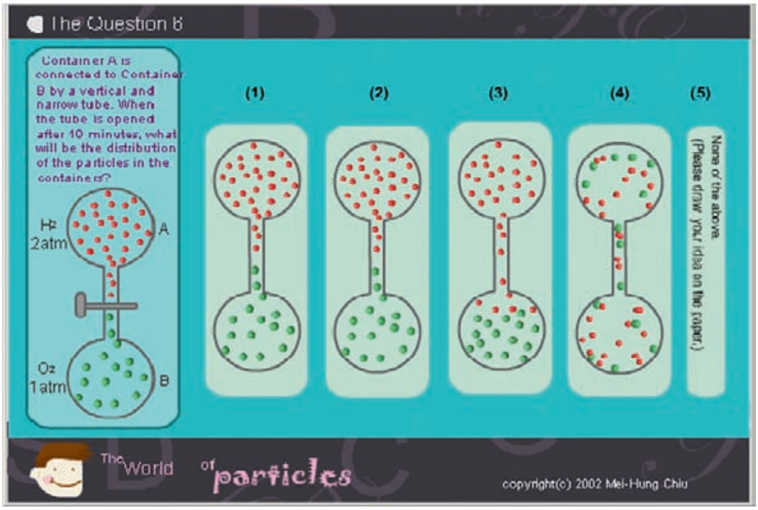


The Question 5

Container A is connected to Container B by a vertical and narrow tube. When the tube is opened after 10 minutes, what will be the distribution of the particles in the containers?

(5) None of the above. (Please draw your idea on the paper.)

Fig. 11.16 The first tier of Question 5



Container A is connected to Container B by a vertical and narrow tube. When the tube is opened after 10 minutes, what will be the distribution of the particles in the containers?

None of the above. (Please draw your idea on the paper.)

Fig. 11.17 The first tier of Question 6

Table 11.1 The correct percentage of students' performance in all questions

	The same pressure			Different pressure			
situation	Q1	Q2	Q3	Q4	Q5	Q6	Q1–Q6
grade	H	V	V	H	V	V	
8th	26	15	23	13	14	26	20
9th	40	23	30	17	20	27	26

H: Horizontal, V: Vertical

In addition, Liang and Chiu found that the students held four mental models: weight model (WM), size model (SM), pressure model (PM), and scientific model (SCM). Students who held WM thought that the way gas particles were distributed depended on their weight. For instance, in the horizontal situation, students thought that the lighter gas particles (H_2) would float in the top part of the container and the heavier gas particles (O_2) would sink to the bottom of the container. In the vertical situation, students thought that the lighter gas particles would stay in the top part of the container and the heavier gas particles would stay in the lower container. Students who held SM thought that the larger gas particles would push their way toward the smaller gas particles. Students who held PM thought that the gas particles would move from a higher pressure to a lower pressure. Finally, students holding SCM believed that the gas particles would become randomly distributed in the container regardless of their weight or pressure. Students who held WM thought that the way gas particles were distributed depended on their weight. For instance, in the horizontal situation, students thought that the lighter gas particles would float on the upper part of the container and the heavier gas particles would sink to the bottom of the container. In the vertical situation, students thought that the lighter gas particles would stay in the upper container and the heavier gas particles would stay in the lower container. Given this result, it was easy to conjecture why the students considered the weight of the gas particles attributed to their distribution in the container. Students who held SM thought that the larger gas particles (O_2) would push their way toward the smaller gas particles (H_2). Students who held PM thought that the gas particles would move from a higher pressure to a lower pressure. Finally, students holding SCM believed that the gas particles would become randomly distributed in the container regardless of their weight or pressure. These models were also represented as choices for each question and validated by more students from the empirical study.

In summary, we found that the students received lower scores on items that were at different pressures than on items with the same amount of pressure. Also, we found that although the students learned the concept of diffusion in their seventh grade biology class, they did not generate the conception of diffusion in a submicroscopic manner. Instead, they tended to conceptualize the diffusion of the particles in a more intuitive way (the heavier object sinking to the bottom of the container) than in a scientific model that was designed to delineate the random nature of the particle motion.

Detailed analyses of each student's responses were conducted in order to understand how consistently students used their mental representations with different types of questions that shared similar concepts. For instance, questions 1 (Q1) and 4 (Q4) showed an identical horizontal apparatus, the only difference being the pressure of the oxygen gases. The analysis revealed that given the change of pressure, 80% of the students who held the correct model in Q1 switched to the wrong models (WM or PM) in Q4. In addition, Q2 and Q5 showed identical vertical apparatuses, again the only difference being the pressure of the oxygen. The same transformations resulted. Therefore, the change of pressure played a major role in influencing students' decisions about the distribution of gas particles, regardless of the orientation of the containers. We also found that the students changed their mental models according to the situation that was presented to them. Therefore, this assessment method uncovered students' internal representations of particles in an explicit way and allowed us to diagnose how consistently the students used their internal representations to solve similar problems.

How well did our teachers know their students' conceptions about the distribution of the particles? In order to answer this question, 31 physical science teachers in junior high schools were asked to predict student performance on the same six items discussed above (Liang & Chiu, 2004). The results revealed that 12% of science teachers believed that students would choose correct answers in the same-pressure situation (Q1–Q3), and 10% of science teachers believed that students would choose correct answers in a different-pressure situation (Q4–Q6). They fully understood the difficulty of generating submicroscopic points of view about particle movement because of the format of the test items were quite unique to them to test submicroscopic nature of the concepts. However, they were not able to predict which items the students preferred. Accordingly, science teachers seem to think that the orientation of the apparatus is more of a factor than the change of pressure. However, researchers found that the effect of pressure is more difficult for students.

With regard to science teachers' predictions in Q1 and Q4, 48% of science teachers thought that students would choose WM in Q1. Fifty-three percent of teachers believed that students would still choose WM in Q4, and 33% believed that students would choose PM in Q4. Researchers found that students' performance is quite similar, regardless of whether it is a horizontal or vertical situation. It seems that science teachers underestimate the effect of the change of the pressure in a horizontal situation for students. As for the consistency prediction by the teachers, one-third of science teachers thought that students should have a consistent mental model in a similar problem situation, whereas only 8–13% of students could use a consistent model (PM) when they faced questions involving the change of pressure. The most striking result was that science teachers are over-optimistic in thinking that students would use a consistent model for solving questions.

Case 3

Chi (2007) and Chiu and Chung (2007) further developed a set of computerized diagnostic items to examine students' conceptions about the movement and distribution of gas particles. All the test items were categorized into contextualized or non-contextualized as well as macroscopic or microscopic levels of questions. An entire class with 33 11th graders was involved in a multiple modeling activities situation (including dynamic models for particle motion, needle and balloon experiment, computer simulation experiment, role play, animation instruction, and formula introduction for integration) as a treatment group, whereas 26 11th grade students were treated as a comparative group with normal multiple modeling activities in chemistry class.

Comparing the treatment group to the control group, the ANCOVA statistics show that there was no significant difference between the two groups in the pretest; however, there exists a significant difference between the treatment and control group in the gained scores between the posttest and the pretest. The results show that in terms of the three facets, both groups significantly improved after multiple modeling activities. Also, the treatment group significantly outperformed the control group in the *correctness* and *completeness* perspectives. The results also reveal a significant difference between the two groups in the *consistency* perspective. From the data analysis, we also found that students' mental models of mixed gases were categorized into six models: scientific, molecular weight, volume, attractive force, kinetic, and activity models. Among them, 10 submodels were also identified. The result shows that close to 50% of the students in the treatment group changed to a scientific model after multiple modeling activities; however, 42.3% of the students in the control group still believed that the diffusion of gas particles was due to their kinetic energy rather than random movement in a container at a constant temperature.

Summary

Ravitz (2002) claims that technology in assessment practice could enhance our knowledge of students' performance in various ways that are needed for the twenty-first century, including thinking skills, teamwork skills, communication skills, and collaborative skills. Quellmalz and Kozma (2003) propose an ICT assessment framework that incorporates the explicit examination of technologies in supporting, extending, and transforming students' learning. This research-based model, the Coordinated ICT Assessment Framework, covers the consideration of subject matter domain (content knowledge and problem-solving demands) and ICT tools and strategies. In particular, using technology to support a formative assessment could be seriously considered.

In the cases we discussed above, students revealed their lack of knowledge of the random distribution of particles, which was consistent with much previous research. This study not only revealed the mis-representation of the diffusion of gases, but also showed the inconsistent mental models that the students held while solving the problems. The result provided some evidence in favor of research that attributes students' learning in relation to the context while facing various types of questions. However, this result does not support Vosniadou's framework theory (1994), which implies a consistent mental model used by learners in her study.

Accordingly, descriptive or pictorial representations in current textbooks may not explain the dynamic and random nature of particles accurately or sufficiently or may introduce more alternative concepts about the distribution of particles. In addition, these studies suggest that the gap between students' performance and teachers' predictions should be appropriately filled in. For instance, the studies discussed above reveal that teachers have over-estimated students' performance on the submicroscopic conceptions that were rarely stated explicitly in science teaching. Science teaching at the lower secondary schools still emphasizes the macroscopic level of understanding rather than the interaction between symbols, phenomenon, and submicroscopic representations. How we could link these triplet representations via multimedia activities is a challenge to science educators as well as to science researchers. In the future, it is necessary to let teachers know via various channels about students' possible misconceptions. In this way, teachers may avoid some inappropriate teaching strategies and analogies. Besides the examples we presented above for assessing students' conceptual understanding of particles, there exist more cases that apply ICT in assessing students' learning in science.

Multimedia as an Instructional Tool

As many researchers have pointed out, models provide some means of visual representation (Woody, 1995), development of historical models in science (Oversby, 2000; Justi, 2000), and linkage between phenomena, expressed models, and mental models (Buckley and Boulter, 2000). Models and modeling play central roles for chemists in their mental activities as well as in their laboratory work. However, the role of models in chemistry has been underestimated in school teaching. Given the way models are used in science classrooms, it is not surprising that students lack experience developing, using, revising, and evaluating their modeling ability. It is also understandable that students have difficulties with models in chemistry learning (Gilbert & Rutherford, 1998). Therefore, multimedia could serve as an instructional tool to help students develop their conceptions of models, to access the models they construct in their minds, and to appreciate the roles of models in chemistry learning both in the classroom and in the laboratory. The following introduces some researchers' work for creating an environment with multimedia for instructional purposes.

Jones (1999) claims that learning chemistry requires not only reading about but also designing and constructing the world of fundamental principles and complex phenomena. She suggests that the use of The Exploring Chemistry lessons, multimedia computer-based simulated laboratory experiments, can provide students with the opportunity to design and carry out many experiments in chemistry in order to enhance their learning of concepts and laboratory techniques in a short period of time. Jones and Persichitte (2001) question whether or not all students benefit equally from the use of a multimedia Goal-Based Scenario (GBSs, Schoenfeld-Tacher, Persichitte, & Jones, 2001) lesson that supports a constructivist approach to learning by matching needs and preexisting knowledge through the use of a realistic context within which the concepts can be assimilated. Agapove, Jones, Ushakov, Ratcliffe, and Martin (2002) further encourage that secondary school students learn chemistry through ChemDiscovery, design activities offered in a technology-based and inquiry-oriented learning environment. The curriculum provides a structured learning environment that allows students to work together in pairs or in cooperative learning groups to conduct inquiry activities. Study results show that students not only work independently, but they become more successful learners with active learning strategies, organizing and reviewing their knowledge and monitoring their understanding when using this curriculum.

Multimedia-Based Instruction Environment

Ardac & Akaygun (2005) designed a multimedia-based instruction environment (films, pictures, drawings, video, and molecular animations), incorporating additional dimensions (visual elaboration and presentation mode), to investigate how instructional conditions could facilitate students' understanding of properties of matter (its nature as well as physical and chemical changes and the relationship among macro, submicro, and symbolic representations. The most prominent feature of the instructional software was based on visual elements that enabled students to relate changes at macro and submicro levels. Three instructional conditions were itemized as follows:

- Condition 1: Dynamic visuals (multimedia) depicting macro-(sub)micro-symbolic representations are presented on an individual basis.
- Condition 2: Dynamic visuals (multimedia) depicting macro-(sub)micro-symbolic representations are presented through whole class instruction.
- Condition 3: Static visuals (multimedia) depicting macro-(sub)micro-symbolic representations are presented through whole class instruction.

The result of ANCOVA using pretest scores as a covariate indicates a significant main effect for instruction. The students who worked under condition 1 and condition 2 significantly outperformed the students in condition 3. In other words, the students who worked with the dynamic representations showed significantly higher gains than the students who worked with the static visuals. However, as long as the dynamic visual displays were used, no significant difference was found. In addition, the majority of students (75%, 12 students) in condition 1 were consistent in their use of particulate drawings in representing matter at the molecular level, whereas less than one-half of the students in condition 2 (44%, seven students) and condition 3 (47%, eight students) were able to make consistent use of particulate drawings in their work. Furthermore, and most inspiring for both dynamic groups, the frequency of the responses was highest for “congruent (if all presentations were correct and in agreement with each other)” responses for conditions 1 and 2 compared with the other two perspectives, contradictory and incomplete–incorrect. The students under condition 3 showed a high frequency for choosing “incomplete–incorrect” responses. Students who used dynamic visuals on an individual basis (condition 1) produced fewer “contradictory” responses compared with the students who received whole class instruction (condition 2). This study, then, revealed two major contributions of the multimedia environment that was designed: it promoted students’ conceptual understanding at both the macro and submicro levels and it helped students develop a consistent and correct structure of matter mentally.

Hypermedia

Multimedia and hypertext have been around for a while now. The combination of multimedia and hypertext for the purpose of creating a meaningful hypermedia environment in chemical education might be of some value. Ebenezer (2001) elaborates on the features and values of a hypermedia environment to elicit students’ understanding of the solution process of table salt. The environment Ebenezer designed allows students to use a drawing program to show their own visual representations of dissolving and to link three levels of chemical knowledge, including: “macroscopic” aspects, such as table salt dissolving in water; “submicroscopic,” theoretical concepts and models like the chemical structure of sodium chloride and water (the dissolution process at the particulate level); and the “symbolic system,” $NaCl_{(s)} + H_2O- \rightarrow Na^{+}{}_{(aq)} + Cl^{-}{}_{(aq)}$. In addition, the students were given a booklet called “Personal Chemistry Journal” in which to record their answers, understandings, and feelings. The design of the hypermedia environment also enabled the students to go forward and backward to see connections among different types of knowledge in chemistry: macroscopic, submicroscopic, symbolic, and solution process. The results showed that the hypermedia environment allowed the students to express and represent their conceptions about dissolving with the assistance of animation—to visualize how melting is different from dissolving, how ions are formed, and how hydration takes place. The use of limited-text hypercards provided students with the opportunity to learn from the text as well as to become active learners by generating personal links of the content knowledge. In particular, in subsequent lessons, students were successful in translating their understanding of table salt dissolving in water to the dissolution of other ionic solids in water. In summary, the students indicated a conceptual change in their learning with the hypermedia environment, the use of chemical terms in their written explanations, and the relationship among models and symbols. Nevertheless, there were still three areas of difficulties that the students encountered within the environment: (a) the ion formation, (b) the polar nature of water molecules, and (c) the hydration process.

Other researchers draw more general attention to the possible development of inquiry skills using a multimedia instructional environment. For instance, Lin (2000) claims that the general science curriculum fails to promote learning in science in many countries in part because it is not designed to promote inquiry but, rather, is decreed. Based on the previous studies from the Computer as Learning Partner project (Linn & Hsi, 2000), Linn developed Knowledge Integration Environment (KIE) activities to provide a scaffolding environment to improve students' inquiry skills and to promote lifelong learning that could elicit scientific understanding. The KIE partnership wanted to use the growing wealth of Internet resources to promote an integrated understanding of science. Linn criticized the typical science materials for often ignoring or contradicting the ideas of students and textbook writers and focusing, instead, on providing the right answers. KIE allows students to link, connect, distinguish, organize, and structure their models of scientific phenomena.

Linn further extended her KIE model to the Scaffolded Knowledge Integration (SKI) approach, which offers guidelines to help designers create materials that promote integration. The four guidelines of knowledge integration for the SKI framework are: make science accessible, make thinking visible, help students learn from each other, and promote lifelong science learning. Each feature aims to bring personally relevant materials to one's learning, to make thinking explicit, to enhance one's contribution via online interaction, to promote autonomy, and to link personally relevant problems to class topics using an inquiry process in various contexts. In her series of studies (Linn, Shear, Bell, & Slotta, 1999; Linn, Clark, & Slotta, 2003; Hoadley & Linn, 2000), the use of multimedia materials extend students' scientific literacy to technology literacy and also serve to facilitate the integration of various disciplines, the generation of explanations or arguments relating to evidence in science learning, and the promotion of the collaborative exchange of ideas among learners.

Monaghan & Slotta (2001) notice that despite the amount of literature on the understanding of students' preconceptions as well as on the pedagogy for assisting students' conceptual change, the majority of middle school and high school science teachers still employ more traditional approaches to teaching science. Monaghan and Slotta used the Web-based Integrated Science Environment (WISE) to design an online community for teachers to actively discuss issues concerning constructivist pedagogy and the use of WISE and other technologies as well as to offer support for the use of WISE activities.

In Europe, the Practical Experimentation by Accessible Remote Learning (PEARL) project aims to develop a system to enable students to conduct real-world experiments as an extension of computer-based learning. To use the PEARL system, teachers must be familiar with how to provide tutor–student and student–student interactions for discussion, reflection, and experiment activities. This distance learning with technology also opens an avenue for learning lab work in science.

Technology Pedagogical Content Knowledge (TPCK)

Shulman (1986), a pioneer, introduced the notion of pedagogical content knowledge (PCK)—a teacher's knowledge of how to integrate and transform complex knowledge of learning activities to generate specific knowledge in teaching. Many other researchers have extended his concept of PCK to diverse domains, including subject matter knowledge, contextual knowledge, learners' prior knowledge, and other knowledge related to pedagogical instruction (e.g., Grossman, 1990). Although PCK is well studied in teacher education (Fenstermacher, 1994), it has received relatively little attention in the area of educational technology (Margerum-Leys and Marx, 2004).

Koehler and Mishra (2005) introduce technological pedagogical content knowledge (TPCK) as a way of improving teachers' professional expertise—to help teachers become aware of the complex web of relationships between technologies, content, and pedagogy. They claim that the development of TPCK is necessary to teach technology in contexts that honor the rich connections between technology, the subject matter, and the ways of teaching with technology.

Crawford, Zemba-Saul, Munford, and Friedrichsen (2005) find that prospective teachers hold unaccepted ideas initially. After the use of technology, they are able to acknowledge their own alternative conceptions and become aware of the critical importance of developing a deep, scientifically aligned understanding of their own science content. Margerum-Leys and Marx (2004) investigated how a student-teacher and an in-service teacher, acting as a mentor, developed their professional expertise through constant access to technology. The results revealed that the student-teacher introduced technologically infused activities, which gave the in-service teacher an increased ability to interact with her students electronically during nonschool hours. Hennessy et al.'s (2006) observation of teachers using simulations when they teach found that although the students enjoyed "hands-on" use of the simulation and valued being able to replay experiments and to manipulate variables of an experiment, the students' contribution was limited, and highly structured tasks played a central scaffolding role in the lesson.

As discussed above, there are many ways to make good use of multimedia materials in science teaching. However, teachers did not access resources as we would have expected. Also, the use of high-level technology is still surprisingly low (Ertmer, 2005). In order to teach effectively, a teacher has to know things about the power of technology—not technological content knowledge per se but, rather, a special understanding of technology that provides different functions and channels for meaningful learning.

Summary

Learning chemistry is a complex cognitive activity that requires imagination—a mental effort of constructing and manipulating symbols and models internally in order to link phenomena to abstract concepts. Many studies have made evident the power of multimedia in learning these abstract and complex concepts in chemistry as well as in empowering teachers' instruction. The instructional environments discussed above have features and values covering many perspectives, for instance, animation of the chemistry concepts to depict the submicroscopic nature of particles, dynamic visuals to bridge a phenomenon and the submicroscopic behavior of particles, and hypertext and visuals to relate different representations of a chemistry concept. With these characteristics and values, the instructional environment provided various opportunities for students, for example, to incorporate a substantive amount of information in multimedia that requires students to extract, analyze, manipulate, conceptualize, modify, and evaluate their internal structure of the knowledge. The studies reviewed above indicated that well-designed instruction can foster students' understanding through the use of visual displays that depict representations of chemical phenomena. However, it is not limited only to engaging students in a cognitive activity: well-designed instruction also helps teachers to act as facilitators, helping students to extract and process information more efficiently and meaningfully.

Concluding Remarks and Implications

In the twenty-first century, knowing about and using technology is a universal challenge for all citizens in all parts of the world. School science teachers have the responsibility to cultivate students' literacy in science as well as in technology. Science teachers' knowledge about the role of multimedia in learning, assessment, and instruction should be addressed and emphasized in preservice and in-service professional development. The multimedia studies discussed in this paper have shown evidence of their successful innovation in school science teaching, in particular in chemistry, when they were introduced into schools. The authors intend again to draw readers' attention to the four roles that multimedia effectively play in chemistry education: as a modeling tool, as a learning tool, as an assessment tool, and as an instructional tool to improve school chemistry learning and teaching. Implications for these four areas are elaborated below.

Implications for Multimedia as a Modeling Tool

Many researchers have claimed the importance of models for chemists to develop scientific theories and design laboratory work (e.g., Greca & Moreira, 2000). Schwarts and White (2005) claim that knowledge of modeling includes knowledge of the following: the nature of models, the nature or process of modeling, the evaluation of models, and the purpose or utility of models. One characteristic of modeling ability is that a learner begins to think like a chemist. Developing such a competency takes a long time—and there is no guarantee of success. So, besides traditional methods of teaching, what else can we do to promote mental representations that facilitate learners' understanding of complex phenomena?

To promote understanding, and then act as a scaffolding/modeling tool for learners to construct mental representations, we recommend a well-designed multimedia environment that takes into account theories in cognitive psychology and epistemology, such as the nature of models, mental models, multiple representations, and visualization. Taking students' existing knowledge into account is also crucial for designing multimedia as a modeling tool. Providing multiple representations as one of the advantages of multimedia is important and necessary in order to meet different individuals' needs in learning. Besides these considerations, deep analysis of students' internal representations is also required to improve the quality of learning outcomes while using multimedia. Furthermore, we have to be aware that the multimedia is not going to replace teachers in classrooms, instead it acts as a modeling tool to assist teachers as well as students to construct a coherent and interwoven form in classroom. It has to pinpoint the relationship among different kinds of representations—that is the triplet relationship in chemistry education. It is not a simple job: To construct a relevant context for fundamental and advanced learning in chemistry in a multimedia environment is filled with challenges.

Implications for Multimedia as a Learning Tool

Multimedia technologies have the capability to enhance chemistry learning and support students' understanding of the triplet relationship. Yet, several issues need to be considered when using multimedia tools in chemistry classrooms.

First, each medium uses different symbol systems to convey information. For example, animations can easily show the interactive and submicro nature of chemical changes, and videos allow students to observe macroscopic phenomena that cannot be reproduced in classrooms. Thus, designers and educations need to appreciate the advantages of different media and carefully select them when developing multimedia tools to better support students' learning.

Second, there are student characteristics involved in multimedia learning. Wu et al. (2001) indicate that students prefer to represent chemical entities in certain ways. Additionally, visuospatial abilities play an important role in chemistry learning, and many multimedia tools are highly demanding of cognitive resources (Wu and Shah, 2004). The design of multimedia tools should take students' preferences and visuospatial abilities into consideration so that the tools support all students in learning about the triplet relationship.

Third, teaching practices might also be a factor that affects the effectiveness of multimedia tools. When using technological tools, students could benefit more from teachers who provide timely feedback, articulate expectations, model desired activities, and solve technical problems (Hoffman, Wu, Krajcik, & Soloway, 2003).

Implications for Multimedia as an Assessment Tool

Over 7,700 articles in science education are devoted to examining students of different ages and genders and at different levels with numerous alternative conceptions in science (Duit, 2007). Many types of formats of assessment were developed and utilized, such as traditional methods of multiple choices, open-ended, short answers, and essay, in order to understand how students think, what their structures look like, and what the nature of knowledge is. More recently, Treagust (1988, 1995) proposed two-tier test diagnostic items to push the design of assessment one step further: to collect students' understanding in science. We believe that multimedia is ideal for collecting data as well as individual differences in knowledge structure. Multimedia allowed us to diagnose the components and structure of students' content knowledge and to further analyze students' responses in a more holistic manner. With the merits of multimedia, we were able to design more sophisticated question formats for each individual, accounting for different competencies in learning science. Accordingly, we are able to promote positive outcomes of learning and direct teachers to support science learning. However, it is not easy to capture students' thinking without careful items designed for assessing purposes in science domain. Without knowing the patterns of students' conceptions and flawness of their understanding, even with the flexibility and other advantages of multimedia environment, one still could not create good quality of test items for assessing students' conceptions in science!

Implications for Multimedia as an Instructional Tool

Multimedia has shown its power and value for modeling, learning, and assessment perspectives because of its nature of visualization, multiple links, and multiple and dynamic representations. These characteristics foster conceptual understanding and connections between symbolic representation and problem solving (Kozma et al., 1996). Unfortunately, not many teachers are willing to take this possibility for making their teaching style changed because of their fear or reluctance for changes in classroom (Dori & Barnea, 1997), particularly in technology, which frequently and rapidly changes over a short period of time. We urge teachers to pay more attention to the technology which could serve as a modeling tool, a learning tool, an assessment tool, of course, and as an instructional tool to enhance school science teaching. In addition, teachers must be aware of the ways to adopt multimedia in their teaching. For instance, navigating or surfing around a program's materials might cause students to lose focus. Teachers should be acquainted with the pros and cons of using multimedia as a teaching aid. In particular, teachers should make explicit connections between macroscopic, submicroscopic, and symbolic representations while using multimedia as an instructional tool.

Literature About Students' Conceptions

Agapove, O., Jones, L., Ushakov, A., Ratcliffe, A., & Martin, M. A. V. (2002). Encouraging independent chemistry learning through multimedia design experiences, *Chemical Education International, 3*, 1.

Ardac, D., & Akaygun, S. (2004). Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. *Journal of Research in Science Teaching, 41*(4), 317–337.

Ardac, D., & Akaygun, S. (2005). Using static and dynamic visuals to represent chemical change at molecular level. *International Journal of Science Education, 27*(11), 1269–1298.

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1988). Theories, principles and laws. *Education in Chemistry, May*, 89–92.

Buckley, B. C. (1995). *A case of intentional model-based learning*. Paper presented at the annual meeting of the American Educational Research Association, San Francisco.

Buckley, B. C., & Boulter, C. J. (2000). Investigating the role of representations and expressed models in building mental models. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 119–135). The Netherlands: Kluwer Academic Publishers.

Chan. W. J. (2002). *Investigating the effectiveness of dynamic analogy on learning chemical equilibrium—Eighth graders' conceptual change on ontological nature of concepts and mental models*. Unpublished Master Thesis, Taipei, Taiwan.

Chiu, M. H. (2007). *Promoting Chemical Education via Research And InstructioN-Based/Oriented Work (RAINBOW)*. Paper presented at the 41st IUPAC World Chemistry Congress: Chemistry protecting Health, Natural Environment and Cultural Heritage, Turin, Italy, August 5–11, 2007.

Chiu, M. H., & Chung, S. L. (2007). *Investigating correctness, consistency, and completeness of students' mental models and paths of conceptual change in learning the nature of gas particles via multiple modeling activities*. Paper presented at the ESERA, Molmo, Sweden, August 21–25, 2007.

Chiu, M. L., Chiu, M. H., & Ho, C. Y. (2003). Using cognitive-based dynamic representations to diagnose students' conceptions of the characteristics of matter. *Proceedings of the National Science Council Part D: Mathematics, Science, and Technology Education, 12*(3), 91–99.

Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education, 90*, 1073–1091.

Craik, K. (1943). *The nature of exploration*. Cambridge: Cambridge University Press.

Crawford, B. A., Zemba-Saul, C., Munford, D., & Friedrichsen, P. (2005). Confronting prospective teachers' ideas of evolution and scientific inquiry using technology and inquiry-based tasks. *Journal of Research in Science Teaching, 42*(6), 613–637.

Dori, Y. J., & Barnea, N. (1997). In-service chemistry teachers' training: The impact of introducing computer technology on teachers' attitudes and classroom implementation. *International Journal of Science Education, 19*(5), 577–592.

Duit, R. (2007). *Bibliography – STCSE: Students' and Teachers' Conceptions and Science Education*. Retrieved from http://www.ipn.uni-kiel.de/aktuell/ stcse/stcse.html. Retrieved 2007.10.31.

Ealy, J. B. (2004). Students' understanding is enhanced through molecular modeling. *Journal of Science Education and Technology, 13*(4), 461–471.

Ebenezer, J. V. (2001). A hypermedia environment to explore and negotiate students' conceptions: Animation of the solution process of table salt. *Journal of Science Education and Technology, 10*(1), 73–92.

Ertmer, P. A. (2005). Teacher pedagogical beliefs: The final frontier is our quest for technology integration? *Educational Technology Research and Development, 53*(4), 25–39.

Fenstermacher, G. D. (1994). The knower and the known: The nature of knowledge in research and teaching. *Review of Research in Education, 20*, 3–56.

Gilbert, J. K. (2007). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (ed.), *Visualization in science education* (pp. 9–28). Boston: Kluwer Academic publishers.

Gilbert, J. K., Boutler, C. J., & Elmer, R. (2000). Positioning models in science education and in design and technology education. In J. K. Gilbert and C. J. Boulter (Eds.), *Developing models in science education*, (pp. 3–17). The Netherlands: Kluwer Academic Publishers.

Gilbert, J. K., & Rutherford, M. (1998). Models in explanations Part 2: Whose voice? Whose ears? *International Journal of Science Education, 20*(2), 187–203.

Greca, I. M., & Moreira, M. A. (2000). Mental models, conceptual models, and modeling. *International Journal of Science Education, 22*(1), 1–11.

Griffith, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching, 29*(6), 611–628.

Grosslight, L., Unger, C., & Jay, E. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 38*(9), 799–822.

Grossman, P. L. (1990). *The making of a teacher*. New York: Teachers College Press.

Hennessy, S., Deaney, R., & Ruthven, K. (2006). Situated expertise in integrating use of multimedia simulation into secondary science teaching. *International Journal of Science Education, 28*(7), 701–732.

Hoadley, C. M., & Linn, M. C. (2000). Teaching science through online, peer discussions: SpeakEasy in the knowledge integration environment. *International Journal of Science Education, 22*(8), 839–857.

Hoffman, J. L., Wu, H.-K., Krajcik, J. S., & Soloway, E. (2003). The nature of learners' science content understandings with the use of on-line resources. *Journal of Research in Science Teaching, 40*(3), 323–346.

Johnson-Laird, P. N. (1983). *Mental models*. Cambridge, MA: Harvard University Press.

Johnstone, A. H. (1993). The development of chemistry teaching. *Journal of Chemical Education, 70*(9), 701–704.

Jones, L. (1999). Learning chemistry though design and construction. *UniServe Science News, 14*, 3–7.

Jones, L., & Persichitte, K. A. (2001). Differential effects of a multimedia goal-based scenario to teach introductory biochemistry – Who benefits most? *Journal of Science Education and Technology, 10*(4), 305–317.

Justi, R. S. (2000). Teaching with historical models. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 209–226). The Netherlands: Kluwer Academic Publishers.

Keig, P. F., & Rubba, P. A. (1993). Translation of representations of the structure of matter and its relationship to reasoning, gender, spatial reasoning, and specific prior knowledge. *Journal of Research in Science Teaching, 30*(8), 883–903.

Koehler, M. J. & Mishra, P. (2005). What happens when teachers design educational technology? The development of technological pedagogical content knowledge. *Journal of Educational Computing Research, 32*(2), 131–152.

Kozma, R. B. (2000). The use of multiple representations and the social construction of understanding in chemistry. In M. Jacobson & R. Kozma (Eds.), *Innovations in science and mathematics education: Advance designs for technologies of learning* (pp. 11–46). Mahwah, NJ: Erlbaum.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*, 949–968.

Kozma, R. Russell, J., Jones, T., Marx, N., & Davis, J. (1996). The use of multiple linked representations to facilitate science understanding. In S. Vosniadou, R. Glaser, E. DeCorte, & H. Mandl (Eds.), *International perspectives on the psychological foundations of technology-based learning environments* (pp. 41–60), Hillsdale, NJ: Erlbaum.

Krajcik, J. S. (1991). Developing students' understanding of chemical concepts. In S. M. Glynn, R. H. Yeany, & B. K. Britton. (Eds.), *The psychology of learning science: International perspective on the psychological foundations of technology-based learning environments* (pp. 117–145). Hillsdale, NJ: Erlbaum.

Liang, J. C., & Chiu, M. H. (2003). *Using dynamic representations to diagnose students' conceptions of the behavior of gas particles*. Paper presented at the International Conference on Science & Mathematics Learning, Taipei, Taiwan, R.O.C.

Liang, J. C., & Chiu, M. H. (2004, April). *Comparing students' performance with science teachers' predictions in the behavior of gas particles*. Paper presented at the annual meeting of National Association for Research in Science Teaching, Vancouver, Canada.

Linn, M. C. (2000). Designing the knowledge integration environment. *International Journal of Science Education, 22*(8), 781–796.

Linn, M. C., Clark, D., & Slotta, J. D. (2003). WISE design for knowledge integration, *Science Education, 87,* 517–538.

Linn, M. C., & Hsi, S. (2000). *Computer, teachers, and peers: Science learning partners*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Linn, M. C., Shear, L., Bell, P., & Slotta, J. D. (1999). Organizing principles for science education partnerships: case studies of students' learning about 'Rats in Space' and 'Deformed Frogs'. *ET R & D, 47*(2), 61–84.

Margerum-Leys, J., & Marx, R. W. (2004). The nature and sharing of teacher knowledge of technology in a student teacher/mentor teacher pair. *Journal of Teacher Education, 55*(5), 421–437.

Monaghan, J., & Slotta, J. D. (2001). *Innovative teacher education using the web-based integrated science environment (WISE)*. Paper presented at the Society for Information Technology and Teacher Education International Conference, Norfolk, VA.

Novak, A. M., & Gleason, C. I. (2000). Incorporating portable technology to enhance an inquiry, project-based middle school science classroom. In R. T. Tinker & J. S. Krajcik (Eds.), *Portable technologies science learning in context* (pp. 29–62). Dordrecht: Kluwer.

Oversby, J. (2000). Models in explanations of chemistry: The case of acidity. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education*. Dordrecht/Boston/London: Kluwer academic publishers.

Pallant, A., & Tinker, R. F. (2004). Reasoning with atomic-scale molecular dynamic models. *Journal of Science Education and Technology, 13*(1), 51–66.

Quellmalz, E. S. & Kozma, R. (2003). Designing assessments of learning with technology. *Assessment in Education, 10*(3), 389–407.

Ravitz, J. (2002). CILT2000: Using technology to support ongoing formative assessment in the classroom. *Journal of Science Education and Technology, 11*(3), 293–296.

Salomon, G. (1979). *Interaction of media, cognition and learning*. San Diego, CA: Jossey Bass.

Schank, P., & Kozma, R. (2002). Learning chemistry through the use of a representation-based knowledge building environment. *Journal of Computers in Mathematics and Science Teaching, 21*(3), 253–279.

Schoenfeld-Tacher, R., Persichitte, K. A., & Jones, L. L. (2001). *Relation of student characteristics to learning of basic biochemistry concepts from a multimedia goal-based scenario*. Paper presented at the annual meeting of the American Educational Research Association, New Orleans, LA (ERIC Document Reproduction Service No. ED 440 875).

Schwarts, C. V., & White, B. Y. (2005). Metamodelling knowledge: Developing students' understanding of scientific model. *Cognition and Instruction, 23*(2), 165–205.

Stieff, M., & Wilensky, U. (2003). Connected chemistry-incorporating interactive simulations into the chemistry classroom. *Journal of Science Education and Technology, 12*(3), 285–302.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15,* 4–14.

Treagust, D. (1988). Development and use of diagnostic test to evaluate students' misconceptions in science. *International Journal of Science Education, 10*(2), 159–169.

Treagust, D. F. (1995). Diagnostic assessment of students' science knowledge. In S. M. Glynn & R. Duit (Eds.), *Learning science in the schools: Research reforming practice* (pp. 327–346). Mahwah, NJ: Erlbaum.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education, 24*(4), 357–368.

Tuckey, H., Selvaratnam, M., & Bradley, J. (1991). Identification and rectification of student difficulties concerning three-dimensional structures, rotation, and reflection. *Journal of Chemical Education, 68*(6), 460–464.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. In S. Vosniadou (Guest Ed.), Special Issue on Conceptual Change, *Learning and Instruction, 4,* 45–69.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*(4), 535–585.

Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1994). Research on alternative conceptions in science. In D. L. Gabel, *Handbook of research of science teaching and learning* (pp. 177–210). New York: Macmillan Publishing.

Wilensky, U. (1999). GasLab: An extensible modeling tool-kit for exploring micro- and macro-views of gases. In W. Feurzeig & N. Roberts (Eds.), *Modeling and simulation in precollege science and mathematics* (pp. 151–178). New York: Springer-Verlag.

Woody, A. (1995). The explanatory power of our models: A philosophical analysis with some implications for science education. In F. Finley, D. Allchin, D. Rhees, & S. Fifields (Eds.), *Proceeding of the third international history, philosophy, and science teaching conference* (Vol. 2. pp. 1295–1304). Minneapolis: University of Minnesota.

Wu, H.-K., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching, 38*(7), 821–842.

Wu, H.-K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education, 88*, 465–492.

Xie, Q., & Tinker, R. (2006). Molecular dynamics simulations of chemical reactions for use in education. *Journal of Chemical Education, 83,* 77–83.

Chapter 12
The Application of a 'Model of Modelling' to Illustrate the Importance of Metavisualisation in Respect of the Three Types of Representation

Rosária Justi, John K.Gilbert and Poliana F.M. Ferreira

Abstract The value of models, modelling and visualisation as a basis for developing an understanding of the nature of and the relations between the three levels of representation is discussed. The requirement for and problems in the development of metavisualisation (a fluent capability in visualisation) are presented. Student practical work, closely associated with teacher questioning, is advocated as a way of developing these skills. A 'Model of Modelling' is presented. In order to validate this model, it was applied to the teaching of 'chemical equilibrium', this being a very important topic for which student misconceptions are well documented. Data were collected from six lessons in which the model was applied excessively with respect to the nitrogen dioxide/dinitrogen tetroxide and chromate/dichromate systems. Students developed a good understanding of chemical equilibrium, as shown by the absence of common misconceptions in an end-of-course attainment test. Students acquired an appreciation of the relationship between the three levels of representation. The value of the model of modelling, with its associated pedagogy as a support for the acquisition and use of metavisual capability, was established.

Introduction

Being able to readily switch the focus of thinking between the macro, the sub-micro and the symbolic levels of representation is a core capability for any competent chemist. This status derives from the fact that chemistry is concerned with the transformation of matter at the atomic level. Chemists start their work by either selecting or creating an apparently simple example of the phenomenon in which they are interested. What they can see and manipulate constitutes the macro level of the phenomenon. As chemistry (like all the sciences) is concerned with the production of explanations for observed phenomena, they then try to imagine why the phenomenon behaves as it does. The products of this imagination, tested for validity by the making and testing of predictions about the behaviour of the phenomenon under different circumstances, are at the sub-micro level. Chemistry, again like all the

---

R. Justi (✉)
Federal University of Minas Gerais, Brazil
e-mail: rjusti@uai.com.br

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_13,

sciences, advances by progressively producing ever-more convincing explanations for broader sweeps of phenomena. This advance always includes attempts to quantify what exists or is taking place: this leads to the symbolic level. In short, knowing about the three levels enables the bulk properties, the qualitative explanation of those properties, and the quantitative explanation of them, all to be understood. Moving between these levels enables them to be readily related to each other. It also exemplifies scientific methodology.

Students all too often find this capacity difficult to acquire (Johnstone, 1982). For example, Hinton & Nakhleh (1999) found that a sample of undergraduate students in the USA were able to mentally operate at the macro and symbolic levels, yet had difficulty linking these to the equivalent representations at the sub-micro level. Another study (Treagust, Chittleborough, & Mamiala, 2003) investigated the way that Australian students use sub-microscopic and symbolic representations when providing explanations for chemical phenomena. According to the authors, students' explanations of a given phenomenon were influenced by their ability to recognise different representation forms of that phenomenon and to transfer from one level of representation to another. Kozma & Russell (1997), when investigating expert chemists' and novice students' understanding of various forms of representation, showed that the experts were much better than novices in transforming one mode of representation into another. This facility is a major contribution to the notion of 'expertise' in chemistry.

Studies like the ones briefly commented on above provide evidence that, in order to develop their chemical knowledge, students must know how to use the three levels of representation, how to express such knowledge in different modes of representation, and how to transfer one representation into another when this were necessary to the understanding of particular aspects of a phenomenon. We suggest that if an efficient, effective and economical, general approach to the development of 'three-level fluency' is to be established, it must be based on a cognitive model embedded within a sound view of the nature of science. Such an approach might therefore be based on the notions of models, modelling and visualisation.

A model is one of the main outcomes of any scientific enquiry and hence is a major contributor to philosophy of science. A model may be defined as a simplified representation of a phenomenon (an object, system, event, process) or idea produced for the specific purpose of providing an explanation of that entity, the most important outcomes of which are the production of successful predictions of how it will behave under a range of circumstances (Gilbert, Boulter, & Elmer, 2000). Entities can be modelled at the three levels: at the macroscopic, by representing some of the aspects of the entity that can be seen; at the sub-microscopic, by representing the ideas produced to explain the constitution and behaviour of the particles that constitute the entity; and at the symbolic, by representing the symbols created to simplify the reference to such particles (as, for instance, chemical formulae and chemical equations).

A model is always initially produced in a person's mind – being then called a *mental model*. For communications purposes, it must be expressed in different modes of representation: concrete, verbal, mathematical, visual, gestural or mixtures of these – some of them being static and others dynamic (Boulter & Buckley, 2000). There is not a restricted correspondence between the level of the entity that is being modelled and the mode of representation used to model it. Aspects of the macro and sub-micro levels can be expressed in all the modes of representation, whilst aspects of the symbolic level are generally expressed as in the verbal or mathematical modes. This indicates the importance of the use of the modes of representation in a comprehensive understanding of the three levels in which a given entity can be modelled.

The understanding that a mental model makes possible is a *visualisation* of its structure and behaviour. For instance, a mental model of a phenomenon makes it possible to predict, by means of visualisation, how it might behave in different circumstances. When a scientist places a mental model in the public arena by means of one or more of several modes of representation, s/he is providing an *external representation* of that model. The *internal representation* that another person forms from this is the mental model for that person. One great ambition of science education is that all students' internal representations of a given model will be very nearly the same as the corresponding external representation. This corroborates the special attention given to how students express their models for entities at different levels. In chemistry teaching, in particular, this issue assumes a major relevance because, as most models represent abstract entities, their visualisation must be an essential part of students' understanding. One of the ways to support the exercise of such visualisations is to provide students with opportunities to create and express their own models, namely to involve them in a modelling-based approaches to teaching.

Modelling, defined as the dynamic process of producing, testing, and revising a model, is a core skill in scientific enquiry. Authentic science education, that which is based as closely as possible on scientific practice as educational circumstances will allow, must therefore include the development of the skills of modelling. We suggest that, by facilitating the development by students of personal mental models of each of the three levels of representation and by encouraging them to mentally 'move' between these, they will acquire the core skill mentioned above. This fluent performance in visualisation has been described as requiring and demonstrating *metavisualisation*, namely the ability to acquire, monitor, integrate and extend learning that involves both internal and external representations (Gilbert, 2005). More specifically, metavisualisation involves the demonstration of five capabilities in a wide range of contexts. These are:

1. *Understanding of the 'conventions of representation'* for all the modes and submodes of representation involving all three dimensions that are commonly used in science: One dimension, the use of chemical and mathematical symbols (for these can be regarded as point objects); two dimensions, the use of pictures, graphs and diagrams of all types; three dimensions, the use of material or concrete forms. That is, how these relate to the model being represented and to the representational scope and limitations that ensue;
2. *The capacity to mentally 'translate' a given model between the modes and submodes and between the levels of representation in which it can be depicted*. In so

doing, they will be able to move between the three levels of representation. For example, being able to relate representations of the bulk properties (the macro level), the physical behaviour of individual particles (the sub-micro level), and the statistical behaviour of the properties of these entities as a whole (the symbolic level), of the ‘particulate nature of matter’ to each other, especially in the gas phase;

3. *The capacity to construct a representation in any appropriate mode and sub-mode for a given purpose*. For example, being able to represent the working of an oil refinery in terms of a diagram of its component parts to an explanation of what takes place in terms of molecular transformations and the chemical equations for these;
4. *The capacity to use visualisation as the basis for the construction of predictions of behaviour in respect of a given model*. For example, being able to visualize the sub-microscopic structure of an ionic crystal so as to predict how it will cleave when subjected to an external force;
5. *The capacity to solve novel problems by constructing analogies to already-used visualisations*. (Gilbert, 2008). For example, using Kepler’s model of the Solar System to explain the electronic structure of an atom, in the manner of Bohr, and hence being able to predict, very approximately, the absorption spectrum that it will produce.

In an overview of existing research (Ainsworth, 2008), it has been shown that students have a wide variety of problems in generating and using representations consistently and coherently, particularly when several have to be retrieved/constructed in a given context. Thus, they do not: understand all the nuances of many of the major conventions of representation, let alone the sub-conventions which exist within each of these; grasp the relationship between any given representation and the phenomenon to which it applies; have criteria by means of which to select a representation that is appropriate for a given purpose; understand how to construct an appropriate representation; readily relate different representations of a given phenomenon to each other. In short, research has shown that, for many students, metavisual capability is a difficult skill to acquire.

The nature of these challenges suggests that practical work, allied to a suitable use of cognitive theory and philosophy of science, may be helpful in meeting them. Although practical work by students may have many purposes (Bennett, 2003), its educational value in general is too often hindered by confusion, in respect of any specific practical activity, about which of these purposes is being addressed (Hodson, 1990). Inevitably, the development of the skills of visualisation would be hindered, rather than helped, by practical work for which the purpose was not clear to the students.

Consequently, practical work that may be more successful in supporting the development of metavisual capability would pay explicit attention to

- focusing on those aspects of a phenomenon under study that require explanation provided through sub-microscopic and symbolic representations;

- showing how science provides explanations of progressively increasing insight that apply to ever-more complex examples of a phenomenon;
- appreciating that external representations at the macro level have a distinct and probably only partial relationship to the world-as-experienced;
- showing students that macro-level representations provide them with an entry point to the exploration of the world-as-experienced;
- helping students to generate questions, based on external representations at the macro-level, such that their perceptions of the world-as-experienced are enhanced.

In this chapter, we present an attempt to put these ideas into practice that has three components. First, we use a ‘Model of Modelling’, an external representation of the mental processes that we postulate to be undergone as a person forms a model. Second, this model is exemplified by its application to the design of a teaching sequence about a key topic in chemistry, the understanding of which requires fluency of mental movement between the three levels of representation. Lastly, this application is implemented in such a way that the processes of students’ thought taking place can be monitored.

A Model of Modelling

Several researchers (for instance, Morgan & Morrison, 1999) have recognised that there is no such thing as a unique way to produce models. However, other researchers have discussed the general steps by which they are produced (Clement, 1990; Halloun, 2004). Justi & Gilbert (2002) have produced a ‘Model of Modelling’ framework (Fig. 12.1).

Modelling is represented within this framework as a non-linear process comprising multiple stages, as follows: *Stage 1* (‘Decide on purpose’ and ‘Have experience’): after the definition of the aim(s) of the model (i.e. what it is to explain), it is necessary to acquire information about the entity that is being modelled (from empirical observations and/or from previous knowledge). *Stage* 2 (‘Produce a mental model’): a mental model is constructed from the information acquired by the selection of an adequate source for the model (something from which an analogy could be proposed) and the use of creativity and reasoning. *Stage 3* (‘Express in mode(s) of representation’): this involves the selection of an appropriate mode of representation with which to produce the expressed model. *Stage 4* (‘Conduct thought experiments’): with the mental model created and suitably expressed, the initial testing stage always has a mental phase (known as thought experimentation) which may prove decisive in the evaluation of the model. *Stage* 5 (‘Design and perform empirical tests’): where the processes involved in Stage 4 are successful, empirical experimentation is designed and carried out, provided that the entities involved are amenable to such treatment and if suitable resources exist. Then follows either *Stage 6* (‘Fulfil purpose’): if the model proved to be successful (in terms of its defined purpose), its ‘scope and limitations can then be considered. If Stage 4

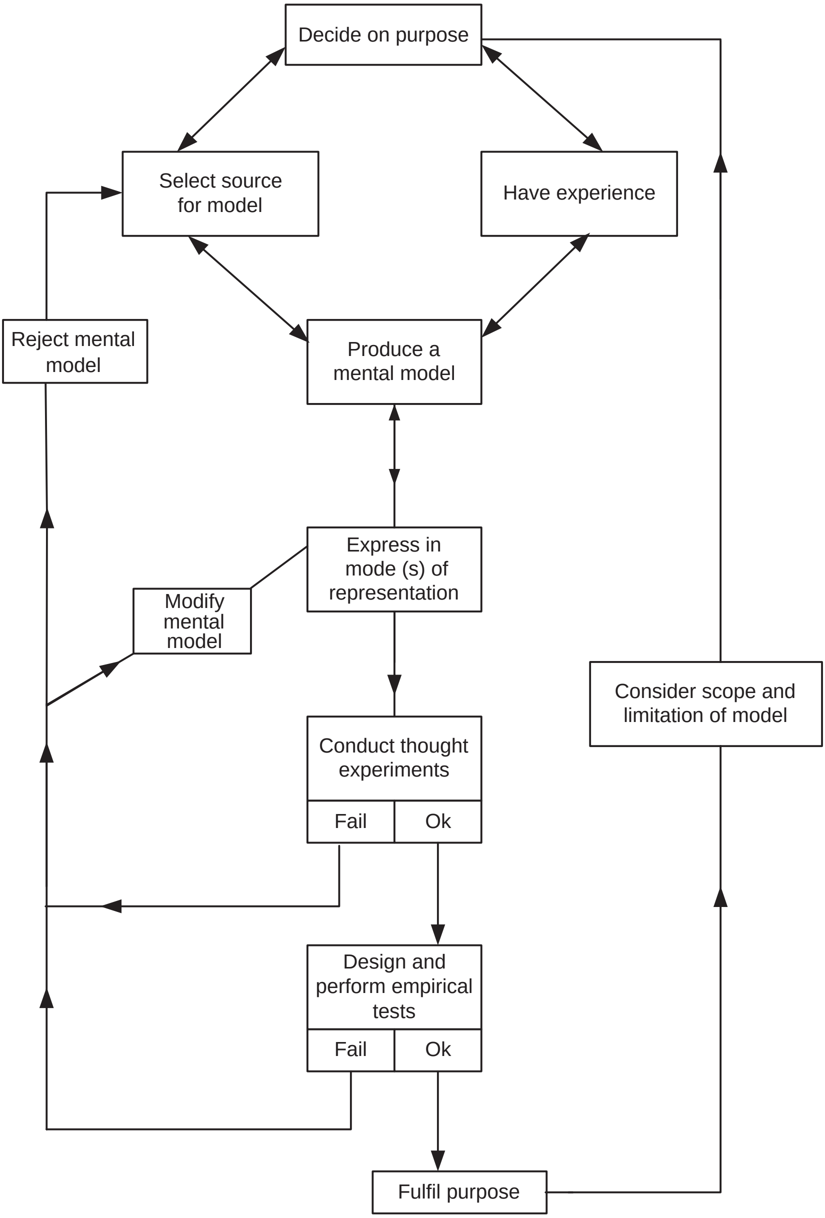


Fig. 12.1 The ‘Model of Modelling’ framework (Justi & Gilbert, 2002, p. 371)

or Stage 5 are unsuccessful, due to the incapability of the model either to explain a given aspect of the phenomenon or to the inadequacy of a prediction made, then *Stage 7* (‘modify or reject mental model’) follows: the model must be altered or a completely new model proposed.

The ‘Model of Modelling’ framework has been used in science teaching in the production of modelling-based teaching activities (for more details, see, for instance Ferreira & Justi, 2005; Justi, 2006; Justi & Mendonça, 2007; Mendonça & Justi, 2005). Essentially, modelling-based teaching consists of lessons framed by the ‘Model of Modelling’ and consisting of activities to support an address to each of the Stages in that model. Such teaching includes the following *pedagogical elements*: gaining empirical evidence; asking, provoking and answering questions; identifying students’ previous ideas; encouraging the expression of models in suitable modes of representation; facilitating discussions about the models and their modes and levels of representation. Our studies have shown that the engagement of students in this kind of activity contributes to more meaningful and participative learning, particularly manifest in an improved ability to comprehend and mentally move between the three levels of representation. This mental process takes place because, in the contexts of these teaching activities, students have the opportunity to experience the interest and excitement of the stages in the production of scientific knowledge, to think about the purposes of science, to create explanations and predictions, to analyse different situations that may result in a need for modifying their initial model. This model has been applied to the topic of ‘chemical equilibrium’. First we present some background about this topic.

Learning About Chemical Equilibrium

The notion of ‘chemical equilibrium’ is central to an understanding of the nature of chemical reactions. An understanding of it involves an appreciation that

- all reactions must be viewed, at least in theory, as being ‘incomplete’, with an equilibrium existing between the concentrations of the reactants and the products;
- when started, the rate of the forward reaction is high but decreases with time as the concentration of the reactants decreases whilst, over the same period of time, the rate of the reverse reaction increases as the concentration of the products increases. At equilibrium, the two are equal;
- changing the conditions of either the forward or reverse reaction causes the extent of the reactions to change until the equilibrium is re-established.

In terms of levels, understanding the notion of ‘chemical equilibrium’ involves being able to mentally ‘translate’ between: the macro level, conceived in terms of the observable properties (e.g. colour); the sub-micro level, conceived as being identities of the specific species involved and their associated behaviour; the symbolic level, this involving being able to both manipulate and understand the 'equilibrium equation', as well as other representations of the process (e.g. graphics).

An excellent overview of the problems that students experience in learning the notions underlying 'chemical equilibrium' is available (van Driel & Graber, 2002). Research shows that conceptual problems arose when students, who had been introduced to chemical reactions through examples that evidently go 'to completion', first met examples of 'incomplete reactions'. In this situation, they

- were often unable to discriminate between reactions that 'go to completion' and those that do not;
- believed that the forward reaction goes to completion before the reverse reaction commences;
- failed to discriminate between the rate and extent of a reaction;
- believed that the rates of both the forward and reverse reaction increase with time until equilibrium is reached.

At a later stage in their science education, presumably after they had been taught about 'chemical equilibrium', older students

- either did not understand the dynamic nature of the equilibrated state or perceived it to be an oscillation between the existence of only reactants and only products;
- had a compartmentalised view, seeing the forward and reverse reactions as acting independently of each other;
- believed that 'mass' and 'concentration' mean the same thing for substances in equilibrium systems;
- believed that the concentrations of the reactants and products were always equal at equilibrium.

In our view, such students' difficulties as described above originate, mainly, from a failure to recognise and teach chemical equilibrium as a *process*. These problems are the outcome of a quantitative approach being taken to the theme to the detriment of understanding chemical equilibrium qualitatively. As a consequence, students have difficulty understanding these and other issues in terms of Le Chatelier's Principle, which demands knowledge about how the processes occur.

Using the 'Model of Modelling' in the Teaching of Chemical Equilibrium

From the 'Model of Modelling' framework and knowledge of students' difficulties in learning chemical equilibrium, we developed a modelling-based teaching sequence for this theme (Ferreira & Justi, 2005). The sequence provides students with opportunities to build, test and rebuild models in order to explain: the occurrence of a given chemical reaction, the reversibility of that chemical reaction, the establishment of a chemical equilibrium in the system under study and the behaviour of the system when the equilibrium is changed. The students were not directly introduced to the modelling framework, but were provided with conditions for developing each of the above-mentioned stages. These stages involved identifying students’ previous knowledge – about both models and modelling and how chemical reactions occurs (in terms of the kinetic particle model) – and the establishment of relationships between such knowledge and the new empirical and theoretical data acquired through the activities provided. In brief, students were involved in the following activities:

Activity 1: Discussing what was to be done (including the fact that the sequence of lessons formed part of a research project), discussing the nature and purposes of models, identifying and developing students’ ideas about modelling. In terms of the ‘Model of Modelling’ this involved ‘having experience’ in everyday life (Stage 1).

Activity 2: Identifying students’ previous ideas about the nature of chemical reaction, building a model for how the transformation of one system in equilibrium – dinitrogen tetroxide (N_2O_4) and nitrogen dioxide (NO_2) – takes place from empirical observations of the system, building a model for how the reverse transformation occurs from these observations, building a model for the system at room temperature. The main aims were to support the development of students’ ideas about the reversibility of chemical reactions – an aspect that was not part of their previous knowledge – and to support the creation of a first model for the equilibrium situation by considering the co-existence of the two species and the dynamics involved. In terms of the ‘Model of Modelling’, this involved ‘having experience’ (Stage 1), ‘selecting a source for the model’, ‘producing a mental model’ (Stage 2) and ‘expressing that model in a suitable mode of representation’ (Stage 3).

Activity 3: Conducting an empirical experiment to observe the transformation of CrO_4^{2-} (chromate ion) into $Cr_2O_7^{2-}$ (dichromate ion), collecting evidence of the presence of both chemical species in the system at any time, building a model to explain the behaviour of the system. In terms of the ‘Model of Modelling’, this involved ‘conducting thought experiments’ (Stage 4), ‘modifying mental model’ (Stage 7), and ‘expressing the new model in a suitable mode of representation’ (Stage 3) for those students who had been able to produce a model including the reversibility in the previous activity. For the other students, this activity involved ‘having experience’ (Stage 1) of another specific reaction, ‘producing a mental model’ (Stage 2) and ‘expressing it in a suitable mode of representation’ (Stage 3). In both cases, in doing so, students extended their ideas about the processes occurring in and the reversibility of a chemical reaction.

Activity 4: Conducting an empirical experiment to observe both what happened when the equilibrium between CrO_4^{2-} and $Cr_2O_7^{2-}$ was modified by adding acid or basic solutions, thus collecting evidence of the presence of both chemical species in the system at any time. This activity led to the use of the previous model to explain what happens when the equilibrium was changed. In terms of the ‘Model of Modelling’, this involved ‘considering scope and limitations of model' (for students who had thought about reversibility since Activity 2; Stage 6), or 'modifying mental model' (Stage 7), and 'expressing the new model in a suitable mode of representation' (for students who had not included the reversibility idea in their models in the previous activity; Stages 2 and 3).

Activity 5: Discussing the relationships between the two systems studied, building a class consensus model for chemical equilibrium, discussing characteristics of such a model, evaluating the teaching approach that had been adopted. Methodologically, the main aim of this activity was to organise all the ideas that students had developed about chemical equilibrium (in essence, to address Stages 1–6 at the same time).

Activity 6: Identifying students' ideas about chemical equilibrium at the end of the above sequence of activities. This task was accomplished through a questionnaire.

Investigating Students' Understanding of the Types of Representation

Aims and Research Questions

The above six teaching activities, used in an ordinary educational context, were investigated in order to probe the influence of the modelling activities on students' learning (Ferreira, 2006). Two research questions guide the current discussion:

1. How did the pedagogical elements provided in support of the modelling-based teaching activities contribute to the development of understanding about the levels of representation, thus to the learning of the nature of chemical equilibrium?
2. What capability did the students have both to visualize the three levels of representation and to move between them, during this modelling-based teaching?

Data Gathering

The use of the modelling-based strategy above described was investigated from an action research perspective by one of us (PF) who was the chemistry teacher of a first grade medium level school class of 26 students (14–15 years old) in Brazil.

Data were gathered during activities described in the six lessons of 100 minutes. In Activities 1–5 (in consecutive lessons) students worked in groups (4–6 students), while in Activity 6 (some weeks later) students worked individually. This teaching approach was adopted to promote students' understanding of how a chemical equilibrium process occurs by supporting the use of empirical observation and discussion (guided by relevant generative questions[1]) of aspects related to the dynamic nature of a chemically equilibrated state – something that is not apparently common in traditional teaching approaches.

Data were gathered from written material produced by the students during the whole process (including the final questionnaire, the video recording of all lessons, and audio recording of the discussions of each group of students).

Data Analysis

Data gathered in the lessons were used to produce case studies for each of the groups of students because such case studies yield rich descriptions of events that are presented in a chronological narrative that incorporates the researcher’s observations. Due to the possible inclusion of such an interpretation of the data, case studies go beyond simple descriptions of the situation and support the analysis of the phenomenon being studied (Cohen, Manion, & Morrison, 2000). In order to discuss the research questions, we browsed the original case studies to identify evidence of how the students dealt with the levels of representation. Whenever it is appropriate, such evidence is included in the later sections of this chapter.

In order to assure the internal validity of the data analysis, two of the authors (RJ and PF) analysed the original case studies (that are written in Portuguese) independently. The results were compared and any disagreement was discussed and resolved. Then all the relevant evidence was translated into English to be discussed with the third author (JG).

Results

The analysis of the case studies showed how students constructed their representations, as well as identified the specific contributions that these representations made to the production of students’ knowledge. Representative examples of both aspects were selected from the case studies.

The Research Questions

In order to organise our discussion, the results are presented separately for each of the research questions. However, due to the emphases being adopted here, we

---

[1] According to Vosniadou (2002), generative questions are those that “cannot be answered on the basis of stored information but require the genuine solution of a new problem.” Therefore, in order to answer a generative question, the subject “must create a mental representation or a mental model” of the entity “and explore it in order to derive from it a relevant answer” (Vosniadou, 2002, p. 358).

decided to include specific aspects of the discussion, and actual examples of students' thoughts and drawings in the context of the second research question.

Research Question 1: How did the pedagogical elements provided in support of the modelling-based teaching activities contribute to the development of understanding about the levels of representation, thus to the learning of the nature of chemical equilibrium?

In order to address this research question, we browsed the original case studies to identify evidence of how the students dealt with the levels of representation and of any possible relationship between such students' activities and any of the elements of the modelling-based teaching. In the following discussion, the most relevant elements of this teaching are emphasised.

We found that the motivation for students' participation in the process of developing their understanding arose from the **empirical evidence** they acquired (from the two initial Activities and those related to the transformation NO_2/N_2O_4) and from the initial challenge to model how the transformation occurred under different temperature conditions. Such models were simple ones because they could be produced only from their interpretations of the empirical evidence together with their previous knowledge. In principle, students could have produced models to represent the process by using the three levels of representation (macroscopic, sub-microscopic and symbolic) in the abstract. However, they had been asked to produce a model that could explain *how* the process occurs, which means that they should propose a sub-microscopic representation. As this question could *not* be answered with the use of students' prior knowledge, the role of experimental evidence was, mainly, to challenge the students to build new knowledge.

The system NO_2/N_2O_4 was used to provide a gradual presentation of new elements that should be incorporated into their models. As students analysed the macroscopic changes of the system, they proposed a series of changes to their previous representations. The observation of the system for the second time (when it was warmed) was crucial for thinking about the possibility of the occurrence of reversibility in the system (since until then the students had dealt only with chemical reactions that occurred in one direction). During the discussion, the equations for both transformations ($2NO_2 \rightarrow N_2O_4$ and $N_2O_4 \rightarrow 2NO_2$) were written at the board by the teacher. This means that students also had access to representations at the symbolic level (at an appropriate moment), which they could integrate into their observations of the empirical systems in producing and representing their models.

The observation of the system NO_2/N_2O_4 provided essential empirical evidence to support the idea that the reactant and product could coexist. According to the questions posed in the activity, this evidence could not only be made explicit in the representation of their models but also be explained by the models. The students who were able to establish relationships between the movement of molecules and the occurrence of a chemical reaction (according to the kinetic particle model that had been studied earlier), were also able to include dynamic components in their models. Those who were not able to do so had the opportunity to think about this from the general discussion of the models – when all groups presented and justified their ideas – or from other empirical evidence that was obtained next.

The system CrO_4^{2-} / $Cr_2O_7^{2-}$ provided students with a new context within which to use the model previously created for the system NO_2/N_2O_4. From this second system students (i) acquired additional evidence about the coexistence of reactants and products in a chemical reaction and (ii) could observe what happened when the equilibrium was changed. This last set of empirical evidence was included in the teaching activities specifically to support the testing of students’ previous models.

One of the differences between the two empirical systems was the complexity of the particles involved in the reactions. As in the previous case, the teacher provided students with the formulae of the species involved and, at an appropriate moment during the discussion of this system, she also wrote the equation $2CrO_4^{2-} + 2H^+ \rightarrow Cr_2O_7^{2-} + H_2O$ on the board. When students tried to use their previous models to explain this system, they found that they had to represent more complex structures. However, this change did not present a difficulty to most of them. On the contrary, the students used the information that the species participating in the second system had more atoms than in the first one to propose interesting mechanisms for the occurrence of the reaction. (More details are presented in the discussion of the second research question.) The concrete representation of the species had an essential role in the production and testing of their models.

In sum, the empirical evidence presented new information about the systems under study, prompting the creation of new expectations concerning the models previously built, and encouraging students to think about the applicability of both the model itself and its modes of representation. These considerations often resulted in a changing of the models in a way as to widen their scope of application to new contexts.

Another element of the modelling-based teaching that was relevant for the development of students’ ideas was **the teacher’s questioning**. Most of the time, this occurred during a discussion between the teacher and a specific group of students. In these cases, the teacher tried to take into account those students’ previous knowledge, models and doubts. At other times, the teacher’s questions were posed to the whole class as she tried to motivate them to think about different explanations – or more complete ones – in order to support the testing of their models. Very frequently, these questions facilitated students’ expression of the codes that were used in their representations, thus allowing for a more comprehensive understanding of both the modelling process in general and the process of building a given representation in particular.

The way that the teacher conducted the lessons contributed to making some details of the systems explicit and helped students in interpreting (i) the empirical evidence, (ii) the questions to be answered by the models, and (iii) the symbolic representations she presented for each system. Moreover, the teacher’s questions supported the students as they tried to remember previous ideas and/or models, to identify the limitations of their models, to propose new models or new explanations for the use of their models in new contexts. Finally, the teachers’ questions were very helpful for increasing students’ confidence in their models.

One of the important elements of the ‘Model of Modelling’ framework is the consideration of the subject’s previous ideas as one of the ‘experiences’ needed to support the proposition of the mental model. In this teaching situation, **students’ previous ideas**, mainly those related to the kinetic particle model, were essential to the inclusion of fundamental attributes in their models (e.g., the dynamicity of the chemical transformation).

The **expression of the models** in different modes of representation occurred during the whole process and, as has been previously commented upon, exerted an essential role in the development of students’ knowledge. This was particularly relevant for those students who could understand the relevance of the choice of a given code and level of representation in order to better express the mental model previously produced. In several activities, students were asked to propose a concrete model for a specific system. This was shown to be essential for the development of students’ ideas because, from the concrete models, they could produce simulations of the chemical process and think about details related to the mechanism of the chemical reactions (such as the directions of the necessary collisions between the molecules, something that they had not studied before).

The **discussion of the models** by the whole class was another element of the teaching process that contributed to students’ learning. During and/or from the general discussion of the models, students could (i) think more deeply about their own models in order to be able to answer the teacher’s and their colleagues’ questions, (ii) share some doubts, (iii) integrate some of their colleagues’ ideas into their models and (iv) appreciate the limitations of their own concrete representations as ways of expressing their mental models.

The aspects previously discussed support the assertion that specific Stages of the modelling-based teaching and the pedagogical elements of support for those Stages both influenced the students’ learning. Alas, inevitably not all students were found to have a clear understanding about all the attributes of the qualitative curricular model they were expected to acquire in the lessons. The models produced by the different groups of students presented particularities that differentiated one from another and which were apparently constructed using different reasoning processes. But we have evidence that, for most of the students, the engagement in the process of producing, expressing, testing, changing their own models, and applying them in different contexts, contributed to a good understanding about how the process of chemical equilibrium occurs in a system. Thus, from their answers to the final questionnaire, we realised that all students understood that a chemical equilibrium is a dynamic process that is established when the velocity of the forward and of the reverse reactions become equal, thus resulting in a coexistence of reactant and product species in the system. No student expressed any of the alternative conceptions related to these elements of the model described in the literature and reviewed earlier in this chapter. The only difficulty some of the students found was in explaining what happens in a chemically equilibrated system when one of the conditions (temperature or concentration of one of the species) is changed. In our view, this could have been the result of two factors (or a combination of them): this specific issue is a complex one and was discussed only in the last class, there perhaps being too little time available; the level of participation of the students in the discussions (with their colleagues in group and with the whole class) was not homogeneous – some did not participate verbally.

In sum, the analysis of the students' learning process showed how each of the elements of the modelling-based teaching (previous ideas, empirical evidence, expression of models, questions, discussions about the models and their modes and levels of representation, etc) contributed to a meaningful learning of the main attributes of a qualitative model for chemical equilibrium. This allowed students to understand the process at the sub-microscopic level and for this to be associated with both the interpretation of the macroscopic evidence and with the use and understanding of adequate symbolic representations. The analysis also provides evidence that each of the Stages and Elements in the modelling-based teaching influenced the development of specific ideas in an idiosyncratic way for each group of students. This corroborates our belief that the dynamic and non-linear process of learning science (particularly chemistry) can be viewed – and fostered – as a process of the successive building and rebuilding of models by the students.

Research Question 2: What capability did the students have both to visualise the three levels of representation and to move between them during this modelling-based teaching?

The data provided the following evidence for the acquisition / deployment of metavisual skills in trans-level migration:

(i) *Mental modelling preceded external representation*: The students were all initially concerned with the building of a mental model. Some groups spent a lot of time discussing their ideas without writing anything or using any concrete materials. However, in all groups, as soon as one student started to make his/her ideas visible, all the other members either continued using that mode of representation or sought a different, better, one. When building the models for the latter system studied, some groups paid special attention to producing an adequate expression of their mental models. During the process of communicating and discussing their models, students realised that the way a model is expressed may change its meaning.

(ii) *External representations were not assumed to be copies of the macro system*: None of the students tried to produce their concrete models for the sub-micro level by using visual characteristics of the macro system. In particular, they used play-dough of colours that were different to those of the macro systems to represent their molecules. In one of the student groups, their written responses emphasised that 'the colour of the system is a consequence of the interactions between molecules; there is no colour for a single molecule'.

(iii) *Different components of various levels of representation were introduced into their models to justify changes occurring at the macro level and explained at the sub-micro level*: Changes in the system observed when the temperature of the NO_2/N_2O_4 system varied were justified in terms of kinetic energy of the molecules. One of the groups used 'movement' symbols to emphasise such differences when they drew their concrete model in the worksheet (Fig. 12.2).

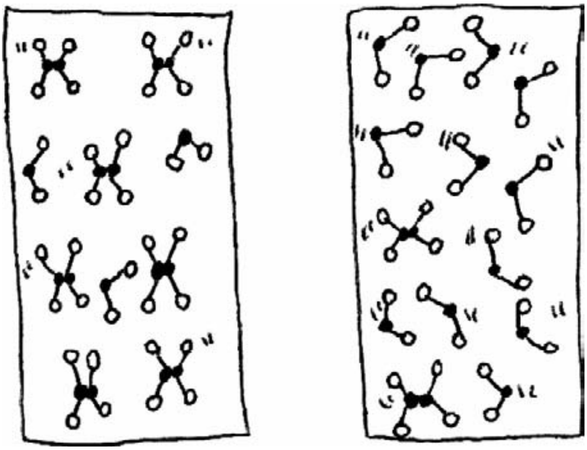


Fig. 12.2 Drawing of the model for explaining the occurrence of the transformation of N_2O_4 into NO_2

Such students explain their model by saying that

> At the beginning of the reaction, molecules have a small kinetic energy that is not enough to break the nitrogen bonds. When the system receives energy, the molecules became more agitated and the bonds between the nitrogen atoms are broken, thus producing NO_2.

(iv) *The role of the symbolic level in the modelling process varied for different students and at different times of the process*: When the data were collected, the students had not yet studied chemical bonding. But they knew the general meaning of symbols and formulas. Therefore, they had no problems in understanding the meaning of N_2O_4 and NO_2 when the teacher wrote them on the board. However, the way the students translated this symbolic representation into other levels changed at different stages of the modelling process. Initially all of them used balls to represent atoms in the correct proportions. Only some of them used sticks to represent bonds. In both cases, they found it very helpful to produce their models from the information obtained from the symbolic model because it made it easier for them to 'see' what was necessary to happen in order to transform one substance into another. Later on, when they were asked to model the system CrO_4^{2-} / $Cr_2O_7^{2-}$, and were faced with the complexity of the structures, one of the groups decided to use only one ball to represent the CrO_4^{2-} ion and a different one to represent the $Cr_2O_7^{2-}$ ion. Being supported by their knowledge about the purposes of models, they justified their choice:

> We produced a single model because here what we want to make evident is the coexistence of the species, nor how one was transformed into another.

When they were challenged by another group to really explain the occurrence of the transformation, they constructed more than one ball and stick representations for each species in order to support the production of their model. Moreover, the students discussed their colleagues' models, making it evident that they had understood other models of representation.

(v) *Explanations were developed by moving between the macro and the sub-micro levels*: In Activity 2, when asked to produce a model for the NO_2 / N_2O_4 initial transformation, all students produced concrete representations of the sub-micro level. However, whilst discussing in groups, some students produced iconic depictions of the phenomena itself, i.e. they drew the initial and the final macro systems showing their different colours. When arguing about the systems with their colleagues, such students pointed to their drawings (rather than to the macro system). However, their discussions were focused on the particles in those systems. Apparently, the students used such drawings as a way to organise the data that they were thinking about. This action shows the importance of empirical evidence in the modelling process.
It should be noted that this kind of drawing (representing the macro level) was done only for the N_2O_4 / NO_2 system. Moreover, it was only used to represent the macro level in the situation above described.

(vi) *Explanations were produced simultaneously at the macro and sub-micro levels*: Later in Activity 2, when the students had observed both the transformations (N_2O_4 into NO_2 and NO_2 into N_2O_4), as well as the system at room temperature, and were asked to produce a model to explain the intermediate colour of the latter system, one group drew beakers with hot and of cold water, both holding a tube containing the gases. They also produced concrete models for the particles of both substances using play-dough (that were put into transparent boxes). During the presentation of their model, they showed (and moved) their concrete representations keeping sheets of paper at the back of the transparent boxes, i.e. they used the representation of both macro and sub-micro elements of the system. The value of translation between the macro and sub-micro levels was shown by these students who, during their presentation, emphasised the role of the temperature changes in the process, the relationship between the temperature of the system and the movement of the molecules, and how specific details of their concrete models were essential in producing and expressing all their written ideas:

> The initial idea was to show that in the hot system the movement of the molecules is more intense than in the cold one. We intend to show that when we shake the molecules from the cold system they would separate: one molecule of N_2O_4 would form two of NO_2. Because of this, we fix the balls representing the nitrogen and the oxygen atoms with sticks – which made the N–O bond stronger in the NO_2 model – and we fix two NO_2 molecules to each other only using play-dough – which would result in a weak N–N bond (thus producing the model for the N_2O_4). We expected that when the system was shaken, the weak bond (between N–N) would easily break whilst the stronger ones (between N–O) would continue existing. Then we would be showing that one molecule of N_2O_4 would form two of NO_2. This explains why the colour of the system is changed.

Students in this group always worked simultaneously with the macro, sub-micro and symbolic levels. They did so trying to make the representation in one level be a support for the development of both a representation in another level and a plausible model that could explain the systems they observed. In Activity 3, when building

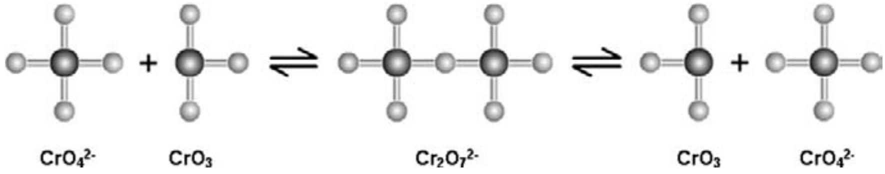


Fig. 12.3 Simulation produced by students to the ‘resonance’ model for the CrO_4^{2-} / $Cr_2O_7^{2-}$ system

their concrete representation for the CrO_4^{2-} / $Cr_2O_7^{2-}$ system, the students realised the importance of focusing on both the dynamic aspect of chemical reactions and the formulae of each ion. Thus, they proposed an original model for the equilibrium that was interpreted as a kind of resonance between those ions and a species that they created (CrO_3). When presenting their model to the class, they made the concrete models produce the ‘resonance’ (as shown in Fig. 12.3) and explained that

> Hydrogen ions (H^+) get one oxygen atom from the dichromate ion (CrO_4^{2-}) producing water and the species CrO_3. As the CrO_3 needs to become stable, it joins a chromate and produces a dichromate ($Cr_2O_7^{2-}$). The system would still contain chromate due to this ‘movement’ of the oxygen atom between two chrome atoms. In the dichromate, the chromate will share an oxygen atom with another chromate that is missing an oxygen atom. So, sometimes the oxygen atom will be forming a chromate, sometimes it will be forming a dichromate. Either one or the other!

This resonance model was a completely different idea that was understood by the class and the teacher only because they enacted a simulation with concrete models. This simulation explained some other details that could not readily be represented (such as the need for stability of the species) for they were always trying to establish relationships with the actual system that they had observed.

(vii) *Predictions were produced from the simultaneous production of explanations at macro and sub-micro levels*: When the students mentioned above shook the boxes containing their models (something that was done only when they presented their model to the whole class) and provided the above explanation, they observed that each of their models for the N_2O_4 molecules could really be split into the models of two NO_2 molecules. In so doing, they realised that the breaking of the bonds did not occur at the same time. Thus, they asserted that the dynamic feature of their model made them think that

> The reaction should occur as time goes by. That is why the change in the system colour was not an instantaneous one.

(viii) *When fluent in understanding, students could rely only on the symbolic level*: In the last activity, when students were asked to produce a model to explain what happened when the equilibrium between CrO_4^{2-} and $Cr_2O_7^{2-}$ was modified, most of them did not construct concrete models. When the teacher asked why they had preferred to only draw their models and to use the symbolic level, they answered:

> Now we can visualize the dynamic system from the drawings. So, we are able to perfectly explain our ideas from the drawings and by using the formulae.

(viii) *When fluent in understanding, students could move freely between the three levels of representation*: In the final questionnaire, students were challenged to explain a new model for chemical equilibrium in general. They were presented with a graphical representation for an equilibrium (the HI / H_2, I_2 system) and had to interpret it in order to answer some questions. In their answers, they were able to interpret the graphical information into both the macro and the sub-micro level. For instance, all the students expressed a clear and correct understanding that the equilibrium is reached when the concentration of all the species are constant (as a result of the occurrence of both reactions with the same velocity). This constant state explained the fact that, when a system is in equilibrium, it is not possible to observe a visible change. Moreover, they emphasised that the colour of the system would show us the coexistence of the particles of all species. For instance, the question involved the equilibrium between a violet gas (I_2) and two other colourless gases (H_2 and HI). A typical comment of the students was

> It (the system) is not completely colourless because there will always be I_2 particles in the system and it is a violet gas.

The students were also able to explain some of that information by using the symbolic level of representation (the equation that was presented together with the graph). This was observed when they made references to the line on the graph, making clear how they were interpreting it in order to reach their conclusions.

Conclusions and Implications

The teaching strategy adopted here led to students acquiring a good level of understanding of ‘chemical equilibrium’, as shown by the absence of common misconceptions in the assessment administered in Activity 6. The sequence of lessons showed that a progressive focus on each of the elements of ‘Model of Modelling’ and on aspects of the notion of ‘chemical equilibrium’ led to that success. This success has qualitatively validated the ‘Model of Modelling’ as the basis for teaching multi-faceted chemical models.

The role of the teacher has been shown to be vital. As students had to express their models for the sub-micro level in a concrete mode of representation, the teacher could identify aspects of their concrete representation (related to the codes of representation or to the ideas they wished to represent) that students did not express verbally. She questioned them, checking what they had really thought at different levels. The concrete expression of the models also allowed students to think about some questions that were not necessarily part of their initial mental models (e.g. the structure of the molecules, the direction of the collisions) – as their attempts to answer the teachers' questions made evident.

From the point of view of the focus of this book, the most important outcome was the demonstration that the use of the 'Model of Modelling' as a basis for producing and conducting teaching activities enabled the students to demonstrate their capability within and between the three levels of representation. Taking each of the five aspects of metavisual capability, given earlier, in turn:

1. *Understanding of the 'conventions of representation'*: From the outset, the students did not assume that their external representations were copies of the observed phenomenon. They progressively employed a range of components in their production of representations at the three levels. Moreover, they were always able to explain the codes of representation they decided to use, and to recognise the scope and limitations of their representations. Progress was made in respect of this aspect; further progress could be expected in situations where the use of a broader range of modes and sub-modes was called for.
2. *The capacity to 'translate' between the levels*: The role of the symbolic level in the production of explanations changed as the sequence of activities was followed, becoming suitably dominant in the later lessons. At the same time, mental 'switching' between the macro and sub-micro levels became ever more fluent. Moreover, during the process, students progressively increase their capacity to decide which level would be more adequate in a given situation.
3. *The capacity to construct a representation for a given purpose*: This was shown. Concrete (material) models were initially used, becoming progressively more sophisticated as the sequence of classes went on. Visual representations (diagrams) were readily employed. Most interestingly, symbolic representations were introduced and coherently used by the students despite the fact that they had not been systematically introduced to the conventions involved.
4. *The use of visualisation to make predictions*: This was done and the predictions tested both empirically and from thought experiments, sometimes with the help of the concrete models previously produced.
5. *The capacity to solve problems by analogy*: In the final questionnaire, the students showed themselves able to apply their understanding of chemical equilibrium to a novel context.

The practical work – the acquisition of empirical data – proved central to the demonstration of these capabilities. In respect of each desirable aspect of practical work, given earlier:

- The choice of specific systems where readily perceived changes of properties were associated with changes in the controlling chemical equilibrium enabled explanation in general and prediction in particular to be linked to behavioural changes.
- The students were able to produce progressively more sophisticated explanations as they experienced ever-more complex systems.

- The choice of systems studied was made so as to allow the ready perception of changes in properties.
- Representing the macro systems being studied evidently gave them a considerable start in producing representations of what was going on at the sub-micro level.
- The role of questions concerning the macro systems generated by the teacher, by individual students, and by groups of students, was a vital part of the processes of producing explanations and successful predictions.

Our conclusion is that a teaching sequence based on the ‘Model of Modelling’ is a valuable basis on which to lead students to a sound understanding of the complex ideas of chemistry and to the demonstration of metavisual capability. A series of conditions are necessary for success. First, opportunity to pose and respond to questions is central. Second, questions posed to and by students at different stages of the process should challenge them and support their creative thinking. Third, practical work that has a clear function in the learning process is vital. Fourth, the systems studied must show perceptible behavioural changes. Fifth, a sequence of carefully chosen systems is necessary.

This study suggests that much more research is needed into aspects of metacognitive capability and into the use of the ‘Model of Modelling’ if we are to provide fuller explanations of the processes involved in ‘understanding the three levels of representation in chemistry’. For example:

- What are the ‘codes of interpretation’ of the modes and sub-modes of representation most commonly used in chemistry? These have never been codified.
- Are there differences between such ‘codes of representation’ used in chemistry and those used by chemistry teachers and textbook authors in producing teaching models? This seems to be a relevant factor influencing the success of teaching models in helping students to understand chemistry curricular models.
- How the understanding of the ‘codes of representation’ influence and are influenced by students’ ability to use virtual models in informal educational contexts (e.g., museums, the internet)? Assuming both the role of virtual models today and the attraction they have for students, a comprehensive understanding of their codes of representation may contribute to increase students’ motivation in learning science.
- How do individual students perceive the process of mentally moving between levels of representation and between modes of representation? Whilst tests of capability to operate within specific modes exist, there is little understanding of the processes involved in ‘mentally moving’ between them.
- What is the relationship between the way students use the three levels of representation and their capability to test their models? As testing models (from thought experiments and/or empirical ways) is an essential stage of the modelling process, their expertise in dealing with the three levels of representation seems to be vital for their learning in modelling-based contexts.

Acknowledgments The authors are most grateful to David Treagust for his invaluable support in presenting our work to best effect.

Rosária Justi acknowledges 'Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq', Brazil, for her personal research grant.

Literature About Students' Conceptions

Ainsworth, S. (2008). The educational value of multiple-representations when learning complex scientific concepts. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education*. Dordrecht: Springer.

Bennett, J. (2003). *Teaching and learning science: A guide to recent research and its applications*. London: Continuum Press.

Boulter, C. J., & Buckley, B. C. (2000). Constructing a typology of models for science education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 41–57). Dordrecht: Kluwer.

Clement, J. (1990). Learning via model construction and criticism. In J. A. Glover, R. R. Ronning, & C. R. Reynolds (Eds.), *Handbook of creativity* (pp. 341–381). New York: Plenum.

Cohen, L., Manion, L., & Morrison, K. (2000). *Research methods in education* (5th ed.). London and New York: RoutledgeFalmer.

Ferreira, P. F. M. (2006). *Modelagem e suas Contribuições para o Ensino de Ciências: Uma análise no estudo de equilíbrio químico*. Unpublished Masters Dissertation, Faculdade de Educação da Universidade Federal de Minas Gerais, Belo Horizonte.

Ferreira, P. F. M., & Justi, R. (2005). *From chemical reaction to chemical equilibrium: Learning through modelling*. Paper presented at the V Conference of the European Science Education Research Association, Barcelona, Spain, 28 August–01 September.

Gilbert, J. K. (2005). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education*. Dordrecht: Springer.

Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education*. Dordrecht: Springer.

Gilbert, J. K., Boulter, C. J., & Elmer, R. (2000). Positioning models in science education and in design and technology education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 3–17). Dordrecht: Kluwer.

Halloun, I. A. (2004). *Modeling theory in science education*. Dordrecht: Kluwer.

Hinton, M. E., & Nakhleh, M. B. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions. *The Chemical Educator, 4*(4), 1–29.

Hodson, D. (1990). A critical look at practical work in school science. *School Science Review, 71*(256), 33–40.

Johnstone, A. H. (1982). Macro- and micro-chemistry. *The School Science Review, 64*(227), 377–379.

Justi, R. (2006). La Enseñanza de Ciencias Basada en la Elaboración de Modelos. *Enseñanza de las Ciencias, 24*(2), 173–184.

Justi, R., & Gilbert, J. K. (2002). Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *International Journal of Science Education, 24*(4), 369–388.

Justi, R., & Mendonça, P. C. C. (2007). *Modelling in order to learn an important sub-micro representation: the nature of the ionic bond*. Paper presented at the VI Conference of the European Science Education Research Association, Malmö, Sweden, 21–25 August.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*(9), 949–968.

Mendonça, P. C. C., & Justi, R. (2005). *Construção de Modelos no Ensino de Ligação Iônica*. Paper presented at the V Brazilian National Science Educational Research Meeting, Bauru, SP, 28 November–03 December.

Morgan, M. S., & Morrison, M. (1999). Models as mediating instruments. In M. S. Morgan, & M. Morrison (Eds.), *Models as mediators* (pp. 10–38). Cambridge: Cambridge University Press.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2003, March). *Why models are advantageous to learning science*. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, Philadelphia.

van Driel, J. H., & Graber, W. (2002). The teaching and learning of chemical equilibrium. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, & J.H. van Driel (Eds.), *Chemical reaction: Towards research-based practice* (pp. 271–292). Dordrecht: Kluwer.

Vosniadou, S. (2002). Mental models in conceptual development. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 353–368). New York: Kluwer Academic and Plenum Publishers.

Chapter 13
Action Research to Promote the Formation of Linkages by Chemistry Students Between the Macro, Submicro, and Symbolic Representational Levels

Vesna Ferk Savec, Irena Sajovic and Katarina S. Wissiak Grm

Abstract This chapter presents findings from an action research project to improve Slovenian primary-school (13–14 years) students' understanding of the role of chemical reactions in everyday life and the meaning of representations at the *submicro* and *symbolic* levels. In the investigation, a teaching approach entitled Life – Observations – Notations (LON) was developed, tested out and evaluated. The action research was conducted in collaboration with primary school chemistry teachers, the adviser for chemistry of the National Board of Education for Slovenia, and researchers in chemical education from the University of Ljubljana. The main findings suggest that as a consequence of the application of the LON approach in classroom teaching (1) students improved their interest in learning about chemical reactions, (2) students gained a more holistic understanding of chemical reactions, (3) students' ability to connect observations at the *macroscopic level* with their understanding of the *submicro* and *symbolic* levels improved, whereby models were used to bridge the gap between *macroscopic* observations and *symbolic* notations of chemical equations and (4) action research contributed to the successful development and implementation of the LON approach.

Introduction

The problems confronting chemistry education in recent decades have been described by different authors (Gilbert, De Jong, Justi, Treagust, & Van Driel, 2002; Pilot & Bulte, 2006). As a consequence of these problems, enrolments in chemistry are in decline in the upper years of school, with serious implications for social and economic development. Gilbert (2006) summarised some of the most pressing problems currently facing chemical education throughout the world as being: overload of content, the presentation of isolated facts, the lack of transfer of facts and ideas to everyday life, lack of relevance to everyday life, an inadequate basis both

---

V.F. Savec (✉)
University of Ljubljana, Ljubljana, Slovenia
e-mail: Vesna.ferk@guest.arnes.si

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_14,

for the more advanced study of chemistry and also for the chemical education of the majority of students who will not continue to study it. Each of these problems poses a series of challenges. One type of address to these challenges has been through the use of ‘context’ as the basis for curriculum design and classroom teaching.

The context-based approach directly targets students’ experience of chemistry curriculum as being abstract, difficult to learn, and unrelated to the world in which they live (Bennett & Lubben, 2006; Bulte, Westbroek, De Jong, & Pilot, 2006; Parchmann et al., 2006; Pilot & Bulte, 2006; Belt, Leisvik, Hyde, & Overton, 2005; Schwartz, 2006). The context-based approach is considered a way to avoid the unsatisfactory outcomes of conventional school chemistry and is based upon the assumption that recognisable contexts appeal to students and provide a ‘need-to-know’ basis for the chemical concepts to be learned. The argument is that through a context, students can give meaning to the chemical concepts that they learn (Bulte et al., 2006). Curriculum development based on the context-based approach generally aims at a more in-depth understanding of a few key ideas instead of the more conventional coverage of scientific content (Pilot & Bulte, 2006). The ‘context idea’ also became a crucial part of a large number of other, more specific, teaching approaches such as project-based, activity-based or inquiry-based science education (Abd-El-Khalick et al., 2004).

Johnstone (2000) believes that the claim that chemistry is difficult to learn and is often not understood by students is connected with students’ incapability to connect the three ‘representational levels’ which originate from the nature of chemistry itself. He believes that the nature of chemical explanation involves three forms of representation which can be thought of as corners of a triangle, whereby no form of representation is superior to another, but each one complements the other. These forms of the subject are (a) the *macro* and tangible: what can be seen, touched and smelt; (b) the *submicro*: atoms, molecules, ions and structures; and (c) the *symbolic*: formulae, equations, molarity, mathematical manipulation and graphs. Gabel (1999) further suggested that the primary barrier to understanding chemistry, however, is not just the existence of the three forms of representation, but is that chemistry instruction relies predominantly on the most abstract, the *symbolic*, type. As a strategy to overcome that problem, Barke (1997) proposed that in the learning process the three corners should be taught one after the other: *macro* type first, structural models on *submicro* type afterwards, and finally chemical symbols on the *symbolic* type. Later on Barke and Wirbs (2002) proposed that students can develop not only knowledge but also images by handling and discussing structural models of matter. Other authors (Chittleborough, Treagust, & Mocerino, 2002; Devetak, 2005; Juriševič, Glažar, Razdevšek-Pučko & Devetak, 2008; Mahaffy, 2004) have developed different models derived from a ‘chemical triangle’. For example, The ‘Interdependence of Three Levels of Science Concepts’ (ITLS) model by Juriševič et al. (2008) shows different levels of interdependence of chemical concepts associated with the visualisation method used in the science classroom and with mental models of chemical phenomena that this approach helps students to develop. Mahaffy's model (2004) claims that understanding chemistry depends on the diverse influences of the society and living environment that shape the teaching and learning of chemistry. His tetrahedron model weaves conceptual knowledge of chemistry with its applications.

Most chemists would agree that the practical experiment is one of the crucial visualisation tools in chemistry teaching and learning at the *macro level* (Gott & Duggan, 1996; Hodson, 1990, 1996; Thulstrup & Thulstrup, 1996; White, 1996). However, from a students' comprehension point of view, researchers (Johnson, 2000; Meheut, Saltiel, & Tiberghien, 1985; Pfundt, 1982) have found that some students do not consider chemical reactions as complete transformations of the matter itself, but only as a change in its appearance or physical state. Consequently, students are not able to make clear distinctions between physical and chemical changes (BouJaoude, 1991). As an answer to these concerns, it was reported (Gabel, 1993, 1998; Russell et al., 1997; Sanger & Greenbowe, 2000; Williamson & Abraham, 1995) that pupils who were taught about physical and chemical changes by implementing *particle*-based schemes achieved a better understanding of the particulate nature of matter, in particular with regard to the distinction between physical and chemical changes, than their peers who were taught the same topics only with the use of textual materials. Another concern, reported by Meheut et al. (1985) and Ebenezer & Erickson (1996), was that chemical reactions can be wrongly perceived as a process of 'mixing' the initial substances, such that the products of chemical reactions are understood as mixtures of the initial substances and their properties as a combination of the properties of the initial substances. According to Johnstone (1991) and Johnson (2002) such misunderstandings occur as the consequence of the relationship between the macroscopic world and the particulate model of matter not being clearly understood. To reduce misunderstandings in the particulate interpretation of chemical changes, Hesse and Anderson (1992) suggested that an understanding of chemical reactions must be introduced as a change in the constituent discrete particles of the initial substances. This strategy promises to foster better understanding of the distinctions between chemical reactions and physical changes. Taber (2001) argued that it would be more productive to start thinking in terms of discrete particles in chemistry education rather than at the level of atoms, provided of course that changes in the discrete particles are not neglected. Another dilemma, that students see the symbolical notations of chemical equations as being independent of chemical reactions taking place, indicating that students do not link the *symbolic* and *macroscopic* types of chemical representations, was targeted by Barke (1982). He attempted to provide empirical support for the practical usage of models when introducing the *symbolical* type into teaching about structure and chemical reactions.

In summary, according to the recommendations of researchers (Hinton & Nakhleh, 1999; Russell et al., 1997; Tasker, Chia, Bucat, & Sleet, 1996), it is crucial to teach about chemical reactions by helping students to draw links between the types of representation. Despite the remarkable value of these research findings, the general impression given is that their implementation in the practice of teaching has not been complete. de Jong (2005) points to a need to bridge the gap between research findings and the practice of teaching. One of the suggested ways to improve the situation is through the use of action research (Gilbert et al., 2002), which is a process in which participants examine their own educational practice systematically and carefully, using the techniques of research (Watts, 1985, p. 118).

The original idea of using research in a natural setting can be traced back to Kurt Lewin in the 1940s, who coined the term ‘action research’ to describe ‘work that did not separate the investigation from the action needed to solve the problem’ (McFarland & Stansell, 1993). The described process was cyclical, involving a ‘non-linear pattern of planning, acting, observing, and reflecting on the changes in the social situations’ (Noffke & Stevenson, 1995). Over the years, numerous articles and books have been written about action research in which the authors developed various classification schemes to compare, contrast and trace the development of the different types of action research in various fields (Calhoun, 1993; Cochran-Smith & Lytle, 1993; McKernan, 1988; McTaggart, 1993; Reason, 1994). In the field of education, Stephen Corey in the mid-1950s was among the first to use action research. He believed that the scientific method in education would bring about change because educators would be involved in both the research and the application of information, so he saw the need for collaboration between teachers and researchers (McFarland & Stansell, 1993). With regard to the aims of action research, in a review study by Kochendorfer (1997), classroom action research was classified into seven groups: seeking quantifiable answers, determining results of change in classroom practice, exploring effects of programme restructuring, discovering whether students can learn to use a process, establishing new professional relationships, developing new understandings in students, and understanding oneself as a teacher. On the other hand, Ferrance (2000) has taken a more technical stance and has classified action research by the number of practitioners involved and the unit of analysis to define: individual, collaborative, school-wide and district-wide action research. A plan of research can involve a single teacher investigating an issue in his or her classroom, a group of teachers working on a common problem, or a team of teachers and others focusing on a school- or district-wide issue. Ferrance (2000) also tried to summarise basic themes within various definitions of educational action research and concluded that the following four can be found in all of them: empowerment of participants, collaboration through participation, acquisition of knowledge and social change. Her representation of the action research cycle involves the following five phases: (1) Identification of problem area, (2) Collection and organisation of data, (3) Interpretation of data, (4) Action based on data, (5) Reflection and evaluation of results and finally the results being used in a new cycle of research. For the purpose of our investigation, Ferrance’s classification and understanding of action research was adopted.

Scope and Context of the Study

Like other countries, the gap between findings from science education research and their implementation in teaching practice has been observed in Slovenia. As an attempt to address that issue an action research project entitled *Partnership between faculties and schools 2006 to 2007: Development of a model of classroom action research for effective teaching of science subjects* was launched. The main aims of the project were the (a) improvement of school practice in teaching science through action research and (b) establishment of efficient action research collaboration between university faculties, school teachers and National Board of Education. Based on the initial analysis of actual problems in school practice from teachers' point of view (Ferk Savec et al., 2007), five main research areas were selected to be investigated and members of the large project team divided to build up certain smaller groups according to their own interest:

- Group 1: Periodic table – a source of information for efficient learning of chemistry,
- Group 2: Development of students' ideas about notations for chemical reactions,
- Group 3: Seaside – understanding the seaside ecosystem with interdisciplinary approach,
- Group 4: Symbolic notations and the mole,
- Group 5: Reactivity of organic molecules.

This chapter deals with the second research area – Development of students' ideas about notations for chemical reactions – which aimed to develop and evaluate a teaching approach, entitled Life – Observations – Notations (LON). In contrast to the traditional approach, our intention in developing the LON approach was to start learning about chemical reactions from discussions about selected everyday life situations, where students would learn to recognise reactants and products and develop observational skills to follow the changes that occur during chemical reactions in everyday life situations as well as in similar examples of chemical reactions in laboratory environment (*macro*). Then we wanted to lead students to write down reactants and products in the form of word equations and further on to present chemical reactions with the use of static models and animations of chemical reactions (*submicro*) towards the use of symbolic notations for chemical reactions and their balancing (*symbolic*). We also aimed to consolidate the knowledge that the students thereby gained. According to the opinion of the LON project team, the teaching of the topic of chemical reactions in Class Eight of primary school (students aged 13–14 years) was a good opportunity to start with such an approach, because at that point students are confronted with the notations for chemical changes for the first time. With regard to Kochendorfer's classification of classroom action research (1997), the above listed aims of our investigation can be classified in two groups: 'assessing the results of change in classroom practice' and 'developing new understandings in students'.

The following research questions were addressed in the investigation:

1. Does the LON teaching approach facilitate students' interest in learning chemistry?
2. Does the LON teaching approach contribute to students' more holistic understanding of chemical reactions?
3. Does the LON teaching approach improve students' ability to connect observations from the *macroscopic* type of representation with their descriptions using the *particle* and *symbolic* types?
4. Does the action research approach taken contribute to the development and implementation of the LON approach?

Our investigation, within Ferrance's (2000) classification of action research, was collaborative action research. The LON project team existed from three groups of partners: Seven teachers from primary schools, six of whom conducted interventions in their schools; the adviser for chemistry from the National Board of Education for Slovenia; and three chemical education researchers from the Department of Chemical Education and Informatics, University of Ljubljana.

Although, the project group worked in close collaboration throughout, each of the groups of partners had specific role in the project:

- Teachers provided a description of current school practice; a collaborative definition of specific problems in teaching about chemical reactions; the actual development of the teaching unit on chemical reactions; collaboration in the development of the Preknowledge Test and the Test of Gained Knowledge; and the conduct of the actual intervention in school practice. In this intervention, each of the teachers completed a reflective diary of actions and comments, passed the raw results of the Preknowledge Test and the Test of Gained Knowledge to researchers from Department of Chemical Education and Informatics, and, after the results had been analysed, participated in the collaborative interpretation of the results so obtained.
- The adviser for chemistry from the National Board of Education for Slovenia reviewed the teaching unit on chemical reactions; engaged in the development of the Preknowledge Test and the Test of Gained Knowledge in collaboration with other partners; and participated in the collaborative interpretation of results.
- The chemical education researchers coordinated the methodology and conduct of the investigation; participated in the collaborative identification of specific problems in teaching about chemical reactions; provided guidelines for the teachers' development of the teaching unit on chemical reactions; reviewed the Preknowledge Test and the Test of Gained Knowledge; conducted the qualitative and quantitative analysis of results from the Preknowledge Test and the Test of Gained Knowledge; presented the results of this analysis to their partners in the project; participated in the collaborative interpretation of results, in the analysis of the teachers' reflections on their experience, and prepared the report on the project, including guidelines for the future development and use of the LON approach.

Methods

Procedure

Our research design, shown in Fig. 13.1, followed the typical action research cycle as proposed by Ferrance (2000) which involves the following five phases: (1) Identification of problem area, (2) Collection and organisation of data, (3) Interpretation of data, (4) Action based on data and (5) Reflection and evaluation of results. Finally, the results are used in a new cycle of research.

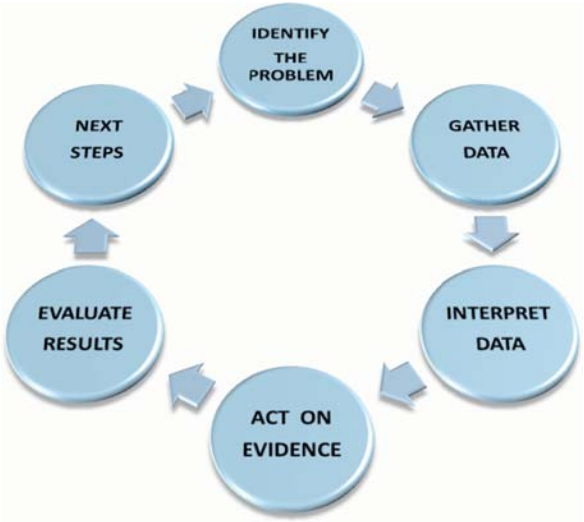


Fig. 13.1 Action research cycle (adapted from Ferrance, 2000)

The particular steps undertaken in our action research are indicated in Table 13.1.

Instruments

Preknowledge Test

The Preknowledge Test was administered before using the teaching unit on chemical reactions. The Preknowledge Test consisted of three tasks with subtasks checking the students' knowledge at the *micro*, *submicro* and *symbolic* types of representation, whereby the maximum score obtainable was 27. Students spent 25 minutes in taking the test. Details of the tasks' purposes and conceptions can be obtained from the authors.

Table 13.1 Description of the research design

Step	Description
Identification of problem area	Based on the initial analysis of actual problems in school practice from teachers' point of view (Ferk Savec et al., 2007) five main research areas were selected for an investigation. A weak understanding of the role of chemical reactions in everyday life was pointed out as one of the key areas that needed to be examined closely.
Collection and organisation of data	Related to the students' comprehension of chemical reactions, two basic problems were pointed out by the teachers: (1) students are not interested in learning because they perceive chemical reactions as isolated facts that are not related to everyday life and (2) students gain a weak understanding of chemical reactions as they primarily experience them as notations at the *symbolic* type, which are not efficiently related to their representations and understanding in the *submicro* and *macro* types. Consequently, a Preknowledge Test for diagnosing the students' success in solving problem tasks involving everyday situations, mainly covering the topic 'linkage of particles', was developed and applied. Students' results from the Preknowledge Test were analysed.
Interpretation of data	Summing up the general findings of the Preknowledge Test led to the conclusion that the majority of students possessed the necessary preknowledge to start learning about chemical reactions, since the average students' successfulness on the test was 73.78%. However students' ability to transfer information between the *macro* type of representation and *submicro* and *symbolic* types had to be improved.
Action based on data	Consistent with the principles of the Life – Observations – Notations (LON) approach, a common teaching unit 'Chemical Reactions' with accompanying teaching materials about chemical reactions in the primary schools was developed and implemented by the participating teachers. During the implementation of the LON approach, reflective diaries were completed by the teachers.
Evaluation of results	Evaluation of the efficiency of the LON approach based on a systematic collection and analysis of the (1) results of the Test of Gained Knowledge and (2) teachers' comments in the reflective diaries describing their feeling about the difference between the new teaching philosophy as compared with the existing one.
Next steps	Based on the results, recommendation and implication guidelines for the future were drawn up.

Test of Gained Knowledge

The Test of Gained Knowledge was administered after using the teaching unit for teaching about chemical reactions. The Test of Gained Knowledge consists of 11 tasks checking the students' knowledge of *macro*, *submicro* and *symbolic* types of representation, whereby the maximum score on the test were 32. Students were allowed to spend 45 minutes taking the test. Details of the tasks' purposes and conceptions can be obtained from the authors.

The Teaching Unit

Description of the Teaching Unit

The teaching unit consisted of four sections, which were optimised and peer reviewed within the LON project team and were published on the project website. All the sections had similar structures with regard to the representational triplet (Table 13.2).

Specific Circumstances in the Participating Schools

All the participating teachers claimed that they tried to carry out the teaching process in accordance to the common LON teaching plan (4 sections – 10 lessons of 45 minutes, 2 lessons per week – 5 weeks of teaching). Since teachers were not able to start the LON teaching process in their schools at the same time due to external factors, the commencement of the teaching in schools varied from November 2006 to February 2007. Consequently, during the conduct of the teaching process, the participating teachers were at very different stages of teaching and the continuous exchange of information among them was not possible. Therefore, after teaching of each of the segments, teachers individually collected the feedback from their students with a special questionnaire and analysed them for their own use in adjusting later episodes of teaching. Those slight adjustments to the common LON teaching plan could be seen from the teachers' entries in their reflective diaries. Teachers also explained that they adjusted the lessons in the light of classroom situations. They probably also did so as well in light of the particular teachers' personal teaching styles and their specific relations with students.

From the contents of the teachers' reflective diaries, the following differences in the lessons provided could be observed: (1) Some teachers added extra exercises in knowledge consolidation, (2) some teachers left out particular activities, (3) some teachers adjusted the duration of particular sections (Fig. 13.2), (4) teachers used different motivational approaches to facilitate learning, e.g. students were rewarded with marks for their success in the Test of Gained Knowledge at the School N° 4. The duration of particular parts of the teaching plan is given in Fig. 13.2.

Teachers' Reflective Diaries

During the action research, teachers wrote their reflective diaries that this procedure helped them to reflect on what they have done with their time, on what they had taught and what they were to teach. In the diary they recorded detailed descriptions of classroom practice. It was also a valuable tool in helping them to deal with emotionally challenging situations. Diaries included entries on what happened during the lessons, what they thought about those lessons and how they reacted to what had

Table 13.2 The teaching unit 'Chemical Reactions'

Section 1: Energy and substance changes at chemical reactions
Section 1 was introduced by a general class discussion about chemical reactions and their consequences in everyday life. As an example of everyday situation a process of cleaning contact lenses was brought up and as its simplified simulation – an experiment entitled 'The secret of cleaning of soft contact lenses' – was carried out as a wet laboratory task in groups of students (*macro level*). Then teachers explained the presented chemical experiment using submicro representations with a simple computer animation and the students assembled the corresponding 3D models (*submicro*). Afterwards the representation of chemical reactions by writing word and symbolic equations introduced, and finally the energy diagram of a given chemical reaction was introduced (*symbolic*). Through various students' activities some further examples of chemical reactions in all three types (*macro level, submicro level, symbolic*) were presented and discussed.
Section 2: Fuel cells as an alternate energy source
This section started with a class discussion about selected examples of chemical reactions where energy is released in a form of light, heat or sound. As an example of an everyday situation, an article about the world's first fuel cell-powered train was used. A chemical experiment called 'Cracking soapy water bubbles' was then carried out as a wet laboratory demonstration (*macro*), and explained as a *submicro* representation by the use of an animation, followed by 2D presentation with models. Afterwards word and symbolic equation of the presented chemical reaction were derived and the energy diagram of a given chemical reactions was presented (*symbolic*). At the end, knowledge was transfered to some other examples of chemical reactions dealing with energy changes (*macro level, submicro level, symbolic*).
Section 3: The importance of water softening
This section began with a class discussion about the importance of water softening and the different factors that influence water hardness. As an example of everyday situation, the efficiency of dishwasher 'Finish salt' was presented. A set of short chemical experiments entitled 'Testing the dishwasher Finish salt' was carried out as a wet laboratory task in groups of students (*macro*). Later on teachers explained one of those chemical experiments by the use of an animation and also by its 2D presentation with models; then students in groups tried to write 2D representations for other chemical experiments (*submicro*). Students also tried to write down word and symbolic equations and to select the appropriate energy diagrams (*symbolic*). The results of students' work were discussed and corrected when necessary.
Section 4: Electric energy
This section was introduced by a class discussion about some crucial energy-related processes and several issues related to electricity generation. As an example of an everyday situation, the electrolysis of water as an electrolytic process that decomposes water into oxygen and hydrogen was analysed and presented through experimentation (*macro*). Teachers afterwards explained the presented chemical experiment with the use of an animation, and students derived its 2D presentation with models (*submicro*). Afterwards students were encouraged to derive a word and symbolic equation and to propose an energy diagram of a given chemical reaction (*symbolic*). The results of students' work were discussed and corrected when necessary.
Consolidation of knowledge
The knowledge was consolidated on further examples of chemical reactions (*macro level, submicro level, symbolic*).

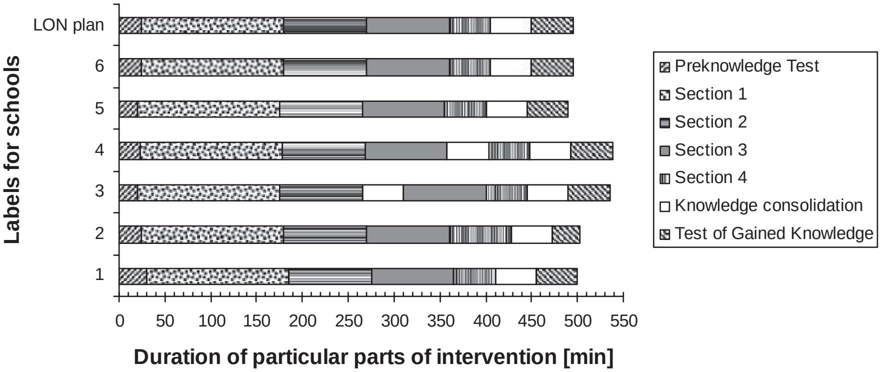


Fig. 13.2 Duration of particular parts of intervention according to the LON teaching plan and actual lessons implementation in particular schools

happened. Entries on differences in the teaching of selected topics when compared with previous years, the analysis and evaluation of students' questionnaires used at the end of each section, were also included. The students' questionnaires were simultaneously analysed and the results included in these diaries. The feedback information was then used for the improvement of the teachers' work.

The teachers' reflective diaries were confidential to themselves. However, they were all requested to report about their experiences in outline from the reflective diaries, as follows: (1) detailed description of each lesson, (2) differences in classroom practice for each of the conducted lessons with regard to previous year(s), (3) their estimation of the results of each of the lessons in the sense of students' motivation and knowledge, (4) suggestions for changes/improvements for each of the conducted lessons and (5) their general ideas for the improvement of the teaching unit and the LON approach.

Subjects

The unit was taught in six schools. Two hundred and twenty six students (13–14 years) were involved in the action research (120 females and 106 males). To provide anonymity of participants and to avoid competition between the participating schools, the schools were labelled 1 to 6.

Data Analysis

At the beginning of the field trials, the Preknowledge Test and the Test of Gained Knowledge were manually processed: later on data were processed by MS Excel. The outlines of the reflective diaries were carefully read through, teachers' statements categorised, and the most representative statements extracted.

Results and Discussion

The main outcomes of the analysis of knowledge tests (details of performance on the tests can be obtained from the authors) and teachers' reflective diaries are presented as answers to the research questions.

Does the LON Teaching Approach Facilitate Students' Interest in Learning Chemistry?

In different places in the outlines of teachers' reflective diaries there are statements indicating that students' interest in learning about chemical reactions has increased in comparison to previous years. Teachers mentioned the increase of students' interest in the context of all three main factors that are incorporated in the LON approach, i.e. (1) Everyday life situations as the foundation of the learning process. (2) The learning process involves many students' activities. (3) Chemical reactions are consistently presented in all three types of representation. Consequently, we assume that those three factors are the main reasons for the increased interest of students in learning about chemical reactions. Each of the listed factors is described in detail below:

(1) *Everyday life situations are the foundation of the learning process*: Students understood that chemical reaction go on in everyday life and are therefore of interest to them. That point seemed to be important to all of the participating teachers since in many places in their reflective diaries they made statements like e.g.:

> For the first time I tried to teach about chemical synthesis reactions by challenging students with a question whether, according to their opinion, the synthesis of water could be used as an energy source for vehicles. The classroom discussion was then led towards reading newspaper article dealing with the topics, which proved to be a good motivation for students. In previous years I had demonstrated the experiments of synthesis between magnesium and iodine, and zinc and sulphur, which were not related to everyday life, and therefore gained much less attention by students. [Teacher from School N° 3, Section 2]

> The starting point of the learning process, the cleaning of contact lenses, was a good choice because students showed great interest in learning (connection to everyday life!). [Teacher from School N° 2, Section 1]

(2) *The learning process involves many students' activities*: Students' interest increased because they liked playing an active role in the learning process (e.g. hands on experiments, construction of representations of chemical reactions with the use of models). Those who were not used to such an approach from earlier teaching also improved their experimental skills and gained experiences through the work with models. In the reflective diaries of all the teachers, statements to support this point could be found as follows:

> Students were very motivated by their own conduct of experimental work. None of the students' groups had difficulties in recognizing the signs of chemical reactions, because students helped each other. [Teacher from School N° 3, Section 1]

> At the beginning students were not keen on conducting experiments by themselves, but when they got more experience, they started to enjoy it. [Teacher from School N° 6, Section 3]

> The homework assignments related to everyday life provided excellent students' feedback. Despite not being foreseen in the LON teaching plan, due to great student interest, we prepared an exhibition of different home-made models for the coal-burning reaction. Most students were very inventive in the selection of materials for home made models to represent chemical reaction at the particle level. [Teacher from School N° 3, additional lesson after Section 2]

> The approach puts students in an active role and increases their motivation for learning. Higher cognitive processes are also emphasized, because students have to make the analyses and draw the conclusions. [Teacher from School N° 4, general remarks to the approach]

(3) *Chemical reactions are consistently presented in all three types of representation and links made between those*: Students understand chemical equations as the descriptions of visible substances and the energy changes accompanying them. Their interest in learning increases – chemical equations are perceived as something meaningful and understandable. Interestingly, despite the fact that continuous implementation of the three types of representation is a crucial part of the LON approach, only in the reflective diaries of two teachers (from schools with best results on the Test of Gained Knowledge; School N° 3 and School N° 4) was that factor also regarded as a potential reason for the increase in students' interest. As they stated in the reflective diaries,

> The initial everyday situation (use of fuel cells) was shown to be a valuable starting point for relating observations of chemical reactions to their explanation with models, which is as a foundation for students' better understanding of the notation of a balanced chemical equation. Students are more interested in learning what is meaningful to them. [Teacher from School N° 3, Section 2]

> Students realised that chemical reactions do not only take place in a laboratory but also in everyday life situations and that chemical equations are the descriptions of chemical reactions in chemical language, therefore they did not consider them as something isolated to be learned by heart like was often the case in previous years. [Teacher from School N° 4, general remarks to the approach]

Does the LON Teaching Approach Contribute to Students' More Holistic Understanding of the Content Chemical Reactions?

In the final discussion of the LON team about the implemented teaching approach, teachers were of the common opinion that students' understanding of chemical reactions gained through the LON approach was more holistic than they had experienced during previous years.

However, it was possible to conclude from the analysis of teachers' reflective diaries later on that they were referring to students' holistic understanding of chemical reactions from three different viewpoints: (1) Students' understanding of chemical reactions as something going on in everyday life and which can be described with the use of chemical language both at the *submicro* and the *symbolic level*. (2) Students' successful application of theoretical knowledge in practical examples of chemical reactions. (3) Students' understanding of chemical reaction as involving both substance and energy change.

More detailed descriptions of each of the viewpoints are as follows:

(1) *Students' understanding of chemical reactions as part of everyday life that can be described with the use of chemical language both at the submicro and symbolic levels*: The conjunction of the two characteristics of the LON approach (Everyday situations are the foundation of the learning process + Chemical reactions are consistently presented in all three types of representation) is essential to a holistic perspective on the project. Yet, as mentioned in responding to the previous research question, whilst all the teachers stressed the importance of the involvement of everyday situations in the learning process, only two teachers (from School N° 3 and School N° 4) were also aware of the great importance of understanding chemical reactions using all three types of representation. This holistic awareness was also reflected in their classroom practice, which probably played a crucial role in the improved knowledge of their students (as shown by the Test of Gained Knowledge) in comparison to other schools.

(2) *Students' successful application of theoretical knowledge to practical examples of chemical reactions*: Students were able to use theoretical knowledge about chemical reactions in practical examples from the laboratory as well as in selected examples from everyday life; for example, a recognition of reactants and products as indications that chemical reactions had taken place (presented with all three types of representation!); a recognition of signs that a chemical reaction had taken place; distinguishing between physical and chemical change, etc. Most teachers pointed to one of the above listed at some point in their reflective diaries as illustrated below:

> When a chemical experiment entitled 'The secret of an efficient cleaning of soft contact lenses with a hydrogen peroxide solution' was carried out as a wet laboratory work in groups of students, being good observers, they did not have special difficulties in recognition of hydrogen peroxide as a reactant, and oxygen and water as products. [Teacher from School N° 3, Section 1]
>
> Students overcame an initial lack of experimental skills and were disciplined in conducting the experimental work. They carefully examined the potential signs of chemical reactions in each of the test tubes. [Teacher from School N° 5, Section 3]

The analysis of the Test of Gained Knowledge showed that the great majority of students (Task 1, $f_{(\%)}$=93.36%)[1] was familiar with the *definition of reactants and products* and was also very successful in the *recognition of reactants and products from the descriptions of simple everyday life processes or various wet laboratory*

---

[1] $f_{(\%)}$ represents the percentage of students who successfuly solved the task.

experiments (Task 8.2, $f_{(\%)}$=89.82%). Also, when teachers commented on the results of the Test of Gained Knowledge in the final discussion about the LON approach, they particularly commented that as many as three thirds of the students (as shown by first part of Task 8.1, $f_{(\%)}$ =75.22%) recognised at least one of the *signs of chemical reaction* in the presented description of a new example of the chemical reaction and more then a half of students (Task 8.1 as a whole, $f_{(\%)}$=57.96%) recognised all of the signs of chemical reactions in the presented example. Most of the students (Task 2, $f_{(\%)}$=82.80%) were also very successful in *distinguishing between physical and chemical changes in examples describing simple everyday processes or wet laboratory experiments*.

(3) *Students'understanding of chemical reaction both as substance and energy change*: This is the opposite of the common practice – as stated by the teachers – where, because they are taught separately, the impression developed by students is that substance and energy changes are not related. In the tasks dealing with relation of substance and energy changes in the Test of Gained Knowledge, many students (Task 3, $f_{(\%)}$=69.91%) correctly defined endothermic and exothermic reactions, recognised the right energy change type of chemical reaction from the description from a so-far unfamiliar experiment (Task 9.5, $f_{(\%)}$=53.98%) and choose the appropriate energy diagram for the described chemical reaction (Task 11, $f_{(\%)}$=58.85%). Despite that, surprisingly, in another example (Task 8.3) only 33.19% of students correctly assumed, based on the described fall of temperature, that an endothermic reaction was conducted. In the final discussion about students' results from the knowledge tests, teachers expressed very positive opinions about students' knowledge gain as a consequence of the LON approach. According to the teachers, most students do understand energy changes accompanying chemical reactions in the sense of an absorption or emission of energy, which is a great achievement in comparison to previous years. The lower results on the test are presumably mostly the consequence of students' problems with terminology – distinguishing between terms exo-/endothermic reaction. This explanation can be supported by statements from teachers' reflective diaries such as:

> Students confidently deduced from the experiment that the heat change during reaction after touching the walls of the glass-cylinder. Some students, weaker in chemistry in general, had problems in understanding that the energy of products is lower after the reaction. Relating the explanation to their 'energy before and after gym lesson' explanation supported their understanding and the most of them were then able to draw energy diagrams by themselves. [Teacher from School N° 1, Section 1]
>
> I'm satisfied with the results of the approach: I have noticed the progress in understanding of concepts of energy change and substance change in chemical reactions. Students were able to determine energy or substance changes in most cases. It is surprising that all students understand when heat is absorbed or evolved – they can explain it in their own words. Most students can draw and explain an energy diagram for a particular chemical reaction, but some students still have problems with terminology ('exothermic' and 'endothermic'). In previous years, when energy changes were taught separately from substance changes, students had a lot of problems with the drawing of energy diagrams. [Teacher from School N° 4, general remarks on the approach]

Does the LON Teaching Approach Improve Students' Ability to Connect Observations of the Macro Level with Their Descriptions Using Submicro and Symbolic Types of Representation?

Some tasks in the Test of Gained Knowledge required students to connect observations about the *macro* course of chemical reactions with their notations in the *submicro* and/or *symbolic* types of representation. The results indicate that most students were able to rearticulate the information about reactants and products of a chemical reaction from the textual description of chemical reaction into the form of word chemical equation (textual description of *macro*→ word equation of *macro*: Task 8.2, $f_{(\%)}$=89.82%; Task 9.1, $f_{(\%)}$=87.61%). This action corresponds to the first step in learning to write down chemical equation in the LON approach. It can easily be explained, because teachers described the learning process to be very efficient to this point, as is illustrated below:

> Students were good observers of changes during the experiment and efficient in the recognition of signs of chemical reaction. They carefully inspected which substances were entering the process (reactants) and also quite good in the prediction of possible products. Students did not have problems in arranging the reactants and products in the form of a word equation. [Teacher from School N° 3, Section 1]

Several other tasks in the Test of Gained Knowledge required students to complete the missing parts of a chemical equation on the basis of the accompanying textual description of the experiment. Most of the students were successful in completing a chemical equation in the submicro type of representation (textual description of *macro* → chemical equation in *submicro*: Task 9.3, $f_{(\%)}$=75.22%), on the other hand completing the equation by writing down the correct formula of the missing element or the substance in symbolic chemical equations seemed to cause problems to more than a half of students (textual description of *macro* → chemical equation in *symbolic*: Task 9.2, $f_{(\%)}$=44.69%). The in-depth analysis of those tasks revealed that the decline in students' success in solving the task by use of a symbolic chemical equation was due to missing coefficients in that equation – most students completed the equation correctly (the first part of Task 9.2, $f_{(\%)}$=80.53%), but did not add the coefficients to balance it. The manual analysis of the tests showed that those students did not write any coefficients at all; it could be that they simply forgot to do so after completing the missing parts of the equation. Understanding of the meaning of 'a balanced chemical equation' remains important. It is interesting that more students did pay attention to the equal number of particles on both sides of a chemical equation when writing it down in the *submicro type* than in the *symbolic* type. A possible explanation was given by one of the teachers, who wrote as follows in her reflective diary:

> Using models in learning about chemical equations has proved a successful tool, especially by students with difficulties in concept understanding. By counting the number of atoms in particle representations they better understood the meaning of a balanced equation. Some students still have problems with balancing chemical equations when models are not avail-

> able – especially in cases of searching common multiple to balance chemical equation. [Teacher from School N° 4, general remarks to the approach]

Perhaps as a consequence of failure by some students to understand the meaning of ‘balanced chemical equation’, some had problems with the process of balancing such equations. This finding can be supported by those poor results in tasks on the Test of Gained Knowledge where only balancing of chemical equations, of the *symbolic* type, was required (Task 6.1: $f_{(\%)}$=69.03%, Task 6.2: $f_{(\%)}$=65.49%). The need for consolidation of such knowledge was also brought up in teachers’ reflective diaries, as follows:

> In the next school year I will incorporate more exercises for knowledge consolidation – above all exercises for notations of chemical equations in the *symbolic* type and their balancing. [Teacher from School N° 2, general remarks to the approach]

Despite the general finding from the Preknowledge Test that the majority of students’ had the necessary preknowledge to start learning about chemical reactions (the average students’ mark on the test was 73.78%, including nine students who made no mistakes), students’ ability to transfer information between *macro, submicro* and *symbolic level* is particularly dependant on their preknowledge in ‘drawing the correct model’/‘writing correct formula’ for the certain element/substance and can therefore be the limiting factor in writing down chemical equations. Apparently such gaps in students’ preknowledge remained uncorrected even after learning about chemical reactions. Students’ problems in writing down the correct formula of the missing element/substance could be tracked down in the analysis of the tasks in the Test of Gained Knowledge, where completing the equation was necessary (these tasks are similar to the already mentioned Task 9.2, but in this case where no textual description of a chemical reaction was given). Students’ ability to complete the missing parts was relatively good, but partly depended on the particular chemical equation (success in completing the reactions: Task 7.1: $f_{(\%)}$=70.76%, Task 7.2: $f_{(\%)}$=95.57%, Task 9.2: $f_{(\%)}$=80.53%; successful after balancing a chemical equation: Task 7.1: $f_{(\%)}$=40.27%, Task 7.2: $f_{(\%)}$=85.40% – in this case no real balancing was necessary because all coefficients were 1, Task 9.2: $f_{(\%)}$=44.69%). Obviously, the low final results on those tasks can be ascribed to students’ problems with the balancing of chemical equations (up to approximately 35% decline in students’ success). Writing down the correct formula of the missing element or the substance apparently caused problems to some of the students (up to approximately 30% decline in students’ success). In the final discussion about the LON approach, teachers said that students’ better consolidation of preknowledge about the content element ‘Linking of Particles’ could contribute significantly to students’ better achievements in writing down chemical equations.

In the final discussion about the LON approach, teachers also stated that students’ ability to connect observations from *macro* with their notations at *submicro* and *symbolic* improved in comparison to previous years. They pointed to the importance of the models in learning about chemical reactions. With concern to that issue in their reflective diaries, teachers wrote:

> Students' stressed that it is much easier to write down chemical equation and check whether it is balanced with the use of models, because they can concretely count the number of atoms on each side of the chemical equation. [Teacher from School N° 3, Section 1]
>
> After students conducted the experiments, I didn't observe problems in their writing down of chemical equations neither in the word nor in the symbolic form. I believe this is due to the use of models in learning of writing down chemical equations in previous lessons. [Teacher from School N° 1, Section 3]
>
> Because of using models in the learning process about chemical reactions students' understanding and comprehension of chemical equations are better then in previous years. [Teacher from School N° 6, general remarks to the approach]

However, one of the teachers said that the use of models alone was not enough:

> Making the models did not cause problems to students, but many did not understand why they are doing that. Also, based on the models that they built, students didn't understand the rules for balancing chemical equations – they just rewrote the numbers based on observations of models. [Teacher from School N°2, Section 2]

Such a statement, especially valuable because of its insight, could indicate that some teachers didn't manage to develop a holistic understanding of chemical reactions in their students. In their teaching they probably just used representations of chemical reactions of all three types without emphasising the linkages between them. As already mentioned in answering the second research question, clear indications of teachers' own holistic understanding of chemical reactions was found only in the reflective diaries of two teachers (School N° 3 and School N° 4) whose students also achieved the best results on the Test of Gained Knowledge.

Does the Action Research Approach Taken Contribute to the Development and Implementation of the LON Approach?

According to Watts (1985), in order to improve existing teaching practice with the use of action research, it is crucial to have in mind that teachers work best on problems they have identified for themselves. Also they will become more effective when encouraged to examine and assess their own work and then consider amended or changed ways of working. Therefore in our investigation, the action research was based on the initial analysis of actual problems in school practice from the teachers' point of view (Ferk Savec et al., 2007). Teaching and learning about chemical reactions in introductory chemistry was pointed out as one of the areas that needed to be examined closely. Teachers' opinions about students' comprehension of chemical reactions revealed that two basic problems arise in using the traditional approach: (1) students are not interested in learning because they perceive chemical reactions as isolated facts that and not related to everyday life and (2) students gain a weak understanding of chemical reactions as they primarily experience them as notations of the *symbolic* type, which are not efficiently related with their representations and understanding of the *submicro* and *macro* types.

Teachers expressed their ideas on how to overcome these problems and those ideas were discussed and further elaborated within the wider LON project team.

Such collaborations as represented in the project team have been described by Watts (1985) as important for the success of action research. He pointed out that it is important for teachers to help each other by working collaboratively and that working with external colleagues supports them in their professional development. Our collaborative action research experience support these statements, namely it seems that the success of the investigation is to a great proportion due to the effective collaboration between the involved partners (the specific roles of partners are described earlier).

Our action research targeted only a limited number of the concerns that were perceived as problematic by the participating teachers. After reading the related literature, two aspects were included in the LON approach. Firstly, in order to improve students' interest in learning, ideas from context-based approaches (Belt, 2005; Bennett & Lubben, 2006; Bulte et al., 2006; Pilot & Bulte, 2006; Schwartz, 2006; Parchmann et al., 2006) should be included. Secondly, in order to achieve improvement in student's understanding, chemical reactions should be consistently presented in all three types of representation. Special attention was therefore devoted to the establishment of strong linkages between those types of representation (Barke, 1982; Hinton & Nakhleh, 1999; Johnstone, 1991, 2000; Tasker, 1996; Russell et al., 1997).

It has to be acknowledged that the teaching process was not equally efficient in all participating schools, but it appeared that an action research approach did lead to a significant improvement in the teaching process in all the participating schools. This observation is supported by positive feedback from teachers and their declared willingness to continue with the implementation of the LON approach in years to come as illustrated below:

> I really enjoyed doing the research and I am certainly planning to carry out the LON approach once again. However, I am going to introduce extensive changes in the students' material next year; the theory would be introduced in a more problem-based way and the conclusions would be presented in a more concise and supportive way. Some students really need such supporting material in order to successfully follow the teaching process used. [Teacher from School N°2]

Conclusions and Implications for Teaching

Our investigation attempted to contribute to better students' understanding of chemical reactions and their notations in the introductory chemistry course, where students (aged 13–14 years) in Slovenian primary schools are for the first time systematically confronted with chemical changes. The teaching approach LON developed was designed to provide students with an understanding of chemical reactions as something related to everyday life and also to achieve a more holistic understanding of the content chemical reactions than the traditional approach. Therefore, in the developed teaching unit entitled Chemical Reactions (10 lessons in duration), discussions about selected everyday life situations were used as the starting point of the learning process and then students' knowledge about particular chemical reactions was systematically built by leading the learning process through the three apices of the ‘chemical triangle’; from selected examples of chemical reactions at *macro*, through their representation in *submicro*, towards the use of *symbolic* notations.

The investigation was conducted in the form of collaborative action research in order to bring together the strengths of chemistry teachers, the advisor for chemistry from The National Board of Education for Slovenia, and chemical education researchers from University of Ljubljana, and at the same time to enable a direct transfer of established research findings into teaching practice. According to teachers’ opinion, in comparison with their experiences in previous years, the most important achievements of the LON approach were:

- Students’ interest in learning about chemical reactions increased, which is due to three main factors that are incorporated in the LON approach: (1) Everyday life situations are the foundation of the learning process. (2) The learning process involves many students’ activities. (3) Chemical reactions are consistently presented in all three types of representation.
- Through teaching with the LON approach, students gained more a holistic understanding of chemical reactions. Three aspects of the teaching contributed to this: (1) A focus on chemical reactions as something that is going on in everyday life and can be described with the use of chemical language in both *submicro* and the *symbolic* types; (2) the formation of strong links between theoretical knowledge and practical examples of chemical reactions; and (3) students’ understanding of chemical reaction as involving both substance and energy change.
- Students’ ability to connect observations at the *macroscopic level* with their descriptions using the *submicro* and *symbolic* types of representation improved as a consequence of the LON teaching approach. Teachers attributed the improvement to the consistent use of all three types of representation and to the use of visible models as a tool for bridging the gap between *macroscopic* observations and *symbolic* notations of chemical equations.

With regard to the results of the investigation, it can be concluded that the LON approach is appropriate and can be recommended to be used in teaching about chemical reactions at the introductory level of chemistry teaching. However, the teaching unit Chemical Reactions needs some improvements based on teachers’ experiences from its classroom use. The investigation also revealed that students’ good preknowledge about linking particles is a crucial foundation for their effective learning about chemical reactions; otherwise it can hinder students’ success in writing chemical equations.

Despite the fact that only the first cycle of the action research spiral has been conducted so far, it can be stated that one of the strong aspects of the investigation was the continuous collaboration between chemistry teachers, the adviser from The Board of Education and chemical education researchers. All the involved partners contributed significantly to the investigation’s results with its aim of improving the practice of teaching as its final outcome. For the successful implementation of the investigation’s results in general school practice it is necessary to continue with the established collaboration. This collaboration will enable the team to systematically follow the conduct of teaching with educational research tools, so enabling further evaluation and improvement (further cycles in the action research spiral). As a consequence of that, a wider implementation of the LON approach might be suggested at the national level in the future. When that is done, the substantial support for teachers when they introduce new materials and approaches about the triplet relationship in their classrooms should be provided. Thus, the teachers who make trial use of the materials could give presentations to their peers based on their experiences; trials' teachers or the advisors from The Board of Education could act as advisors to visit schools beginning to intoduce new materials and approaches in order to supportively critique emergent practice; the web portals that include interactive forums could be created, where teachers could ask their peers or experts various questions or exchange experiences; etc.

Acknowledgments The authors would like to express sincere thanks to teachers and the students of the participating schools in particular from Primary school Venclja Perka, Domžale; Primary school Marije Vere, Kamnik; Primary school Belokranjskega odreda Semič, Semič; Primary school Koseze, Ljubljana; Primary school Louisa Adamiča, Šmarje-Sap; Primary school Franceta Bevka, Ljubljana; to the advisor for chemistry at The National Board of Education, and to the wider project team of the project *Partnership between faculties and schools 2006 to 2007: Development of a model of classroom action research for effective teaching of science subjects* for the collaboration and professional advices as well as to The European Social Fund (ESF) and Ministry of Education and Sport of the Republic of Slovenia for the financial support. The authors would also like to thank Professor John K. Gilbert and Professor David F. Treagust for their valuable comments for the improvement of the chapter.

Literature About Students' Conceptions

Abd-El-Khalick, F., BouJaoude, S., Duschl, R., Lederman, N. G., Mamlok-Naaman, R., Hofstein, A., et al. (2004). Inquiry in science education: International perspectives. *Science Education, 88*, 397–419.

Barke, H. D. (1982). Students' experiments with structural models. Empirical evidence for the practical use of models in the introduction of chemical symbols (Schülerversuche mit Strukturmodellen. Empirische Untersuchungen zum praktischen Einsatz von Modellen bei der Einführung von chemischen Symbolen). *CU, 13,* 4.

Barke, H. D. (1997). The Structure-oriented approach. Demonstrated at the example of interdisciplinary teaching spatial abilities. In W. Gräber & C. Bolte (Eds.), *Scientific literacy*. Hamburg: IPN.

Barke, H. D., & Wirbs, H. (2002). Structural units and chemical formulae chemistry education. *Research and Practice in Europe, 3,* 185–200.

Belt, S. T., Leisvik, M. J., Hyde, A. J., & Overton, T. L. (2005). Using a context-based approach to undergraduate chemistry teaching – a case study for introductory physical chemistry. *Chemistry Education Research and Practice, 6*(3), 166–179.

Bennett, J., & Lubben, F. (2006). Context-based chemistry: The Salters approach. *International Journal of Science Education, 28*(9), 999–1015.

BouJaoude, S. B. (1991). A study of the nature of students' understandings about the concept of burning. *Journal of Research in Science Teaching, 28*, 689–704.

Bulte, A. M. W., Westbroek, H. B., de Jong, O., & Pilot, A. (2006). A research approach to designing chemistry education using authentic practices as contexts. *International Journal of Science Education, 28*(9), 1063–1086.

Calhoun, E. (1993). Action research: Three approaches. *Educational Leadership, 51*(2), 62–65.

Chittleborough, G. D., Treagust, D. F., & Mocerino, M. (2002). *Constraints to the development of first year university students' mental models of chemical phenomena*. Teaching and Learning Forum 2002, Focusing on the Student. Retrieved January 30, 2004, from http://www.ecu.edu.au/conferences/tlf/2002/pub/docs/Chittleborough.pdf.

Cochran-Smith, M., & Lytle, S. L. (1993). *Inside/outside: Teacher research and knowledge*. New York: Teachers College.

de Jong, O. (2005). Research and teaching practice in chemical education: Living apart or together? *Chemical Education International, 6*(1). Retrieved January 15, 2006, from http://www.iupac.org/publications/cei.

Devetak, I. (2005). *Explaining the latent structure of understanding submicropresentations in science*. Doctoral dissertation. Ljubljana: Faculty of Education, University of Ljubljana.

Ebenezer, J. V., & Erickson, G. L. (1996). Chemistry students' conceptions of solubility: A phenomenography. *Science Education, 80*, 181–201.

Ferk Savec, V., Dolničar, D., Glažar, S. A., Sajovic, I., Šegedin, P., Urbančič, M., et al. (2007). Teachers' identification of problems in teaching and learning of science (Učiteljeva identifikacija konkretnih problemov pri poučevanju naravoslovnih predmetov). In M. Vrtačnik & I. Devetak (Eds.), *Action research for the improvement of the quality of teaching science (Akcijsko raziskovanje za dvig kvalitete pouka naravoslovnih predmetov)* (pp. 11–34). Ljubljana: Naravoslovnotehniška fakulteta: Pedagoška fakulteta.

Ferrance, E. (2000). *Action research*. Providence: Brown University.

Gabel, D. (1993). Use of the particulate nature of matter in developing conceptual understanding. *Journal of Chemical Education, 70*(3), 193–197.

Gabel, D. (1998). The complexity of chemistry and implications for teaching. In B. J. Frazer & K. J. Tobin (Eds.), *International handbook of science education* (pp. 233–248). Dordrecht: Kluwer Academic Publishers.

Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look to the future. *Journal of Chemical Education, 76*(4), 548–554.

Gilbert, J. K. (2006). On the nature of "context"in chemical education. *International Journal of Science Education, 28*(9), 957–976.

Gilbert, J. K., de Jong, O., Justi, R., Treagust, D. F., & Van Driel, J. H. (2002). General preface. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: towards research-based practice*. Dordrecht: Kluwer Academic Press.

Gott, R., & Duggan, S. (1996). Practical work: its role in the understanding of evidence in science. *International Journal of Science Education, 18*(7), 791–806.

Hesse, J. J., III, & Anderson, C. W. (1992). Students' conceptions of chemical change. *Journal of Research in Science Teaching, 29*, 277–299.

Hinton, M. E., & Nakhleh, M. B. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions. *Chemistry and Materials Science, 4*(5), 158–167.

Hodson, D. (1990). A critical look at practical work in school science. *School Science Review, 70*, 33–40.

Hodson, D. (1996). Practical work in school science: Exploring some directions for change. *International Journal of Science Education, 18*(7), 755–760.

Johnson, P. (2000). Children's understanding of substances, part I: Recognising chemical change. *International Journal of Science Education, 22*, 719–737.

Johnson, P. (2002). Children's understanding of substances, part 2: Explaining chemical change. *International Journal of Science Education, 24*(10), 1037–1049.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning, 7*, 75–83.

Johnstone, A. H. (2000). Teaching of chemistry. Logical or psychological? *Chemistry Education: Research and Practice in Europe, 1*, 9–17.

Juriševič, M., Glažar, S. A., Razdevšek-Pučko, C., & Devetak, I. (2008). Intrinsic motivation of pre-service primary school teachers for learning chemistry in relation to their academic achievement. *International Journal of Science Education, 30*(1), 87–108.

Kochendorfer, L. (1997). Active voice. Types of classroom teacher action research. *Teaching and Change, 4*(2), 157–174.

Mahaffy, P. (2004). The future shape of chemistry education chemistry education. *Research and Practice, 5,* 229–245.

McFarland, K. P., & Stansell, J. C. (1993). Historical perspectives. In L. Patterson, C.M. Santa, C.G. Short, & K. Smith (Eds.), *Teachers are researchers: Reflection and action*. Newark: International Reading Association.

McKernan, J. (1988). The countenance of curriculum action research: Traditional, collaborative, and emancipatory-critical conceptions. *Journal of Curriculum and Supervision, 3*(3), 173–200.

McTaggart, R. (1993). *Action research: A short modern history*. Geelong: Deakin University Press.

Meheut, M., Saltiel, E., & Tiberghien, A. (1985). Pupils' (11–12 year olds) conceptions of combustion. *European Journal of Science Education, 7,* 83–93.

Noffke, S. E., & Stevenson, R. B. (Eds.). (1995). *Educational action research: Becoming practically critical*. New York: Teachers College Press.

Parchmann, I., Gräsel, C., Baer, A., Nentwig, P., Demuth, R., Ralle, B., et al. (2006). "Chemie im Kontext"– symbiotic implementation of a context-based teaching and learning approach. *International Journal of Science Education, 28*(9), 1041–1062.

Pfundt, H. (1982). Untersuchungen zu den Vorstellungen, die Schüler vom Aufbau der Stoffe entwickeln [Investigations of the concepts students develop about the structure of matter]. *Der Physikunterricht, 26*, 51–65.

Pilot, A., & Bulte, A. M. W. (2006). The use of "Contexts"as a challenge for the chemistry curriculum: Its successes and the need for further development and understanding. *International Journal of Science Education*, *28*(9), 1087–1112.

Reason, P. (1994). Three approaches to participative inquiry. In N. Denzin, & Y. Lincoln (Eds.), *Handbook of qualitative research* (pp. 324–329). Thousand Oaks: Sage.

Russell, J. W., Kozma, R. B., Jones, T., Wykoff, J., Marx, N., & Davis, J. (1997). Use of simultaneous-synchronized macroscopic, microscopic, and symbolic representations to enhance the teaching and learning of chemical concepts. *Journal of Chemical Education*, *74*(3), 330–334.

Sanger, M. J., & Greenbowe, T. J. (2000). Addressing student misconceptions concerning electron flow in aqueous solutions with instruction including computer animations and conceptual change strategies. *International Journal of Science Education, 22*(5), 521–537.

Schwartz, A. T. (2006). Contextualised chemistry education: The American experience. *International Journal of Science Education, 28*(9), 977–998.

Taber, K. S. (2001). Building the structural concepts of chemistry: Some considerations from educational research. *Chemistry Education: Research and Practice in Europe, 2,* 123–158.

Tasker, R., Chia, W., Bucat, R., & Sleet, R. (1996). The VisChem project – visualising chemistry with multimedia. *Chemistry in Australia, 63*(9), 395–397.

Thulstrup, E. W., & Thulstrup, H. D. (1996). *Research training for development* (pp. 320–327). Roskilde: University Press.

Watts, H. (1985). When teachers are researchers, teaching improves. *Journal of Staff Development, 6*(2), 118–127.

White, R. T. (1996). The link between the laboratory and learning. *International Journal of Science Education, 18*(7), 761–774.

Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. *Journal of Research in Science Teaching, 32*(5), 521–534.

Chapter 14
Towards a Coherent Model for Macro, Submicro and Symbolic Representations in Chemical Education

John K.Gilbert and David F. Treagust

Abstract The case is made that, whilst all school-age students should appreciate the nature of and relationship between the macro and submicro types of representation (what we call the *Group A Curriculum*), only those students intended to study chemistry at an advanced level need to know about the quantitative aspects of symbolic representations (what we call the *Group B Curriculum*). The chapters in this book, together with a framework for effective curriculum change, are used to outline what needs to be done if a revised education in respect of a representational triplet is to be provided.

Introduction

We introduced this book by advocating the importance of the triplet relationship that which involves the macro, submicro and symbolic types of representation as a model for chemical education. We asked the authors of the separate chapters to address three aims:

1. The ways that the learning of the three types of representation, taken singly, can be supported;
2. The ways that a capability to mentally move between these three types of representation can be supported;
3. Approaches to the design of curricula that can facilitate effective student learning in respect of the triplet relationship.

The outcome of this work is that the chapters have collectively addressed four themes. Firstly, they have demonstrated the importance of the 'triplet relationship' in chemistry i.e. that which involves the macro/submicro/symbolic types of representation. Secondly, they have brought together and reviewed research literature that shows that students of all ages have problems in understanding those forms of representation and their relationship to each other. Thirdly, they have analysed the underlying causes for those problems stemming from the historical development of

---

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

J.K. Gilbert, D. Treagust (eds.), *Multiple Representations in Chemical Education,*
Models and Modeling in Science Education 4, DOI 10.1007/978-1-4020-8872-8_15,

the forms of representation and from the ways that they are taught. Fourthly, they have pointed out solutions to be implemented if an adequate triplet relationship is to reassert its rightful place as a model for chemical education and no longer be a source of student antipathy towards chemistry as a subject. The key issue is what should be done about these problems, challenges and solutions. In discussing this issue, we draw largely on the chapters in the book with some augmentation from additional sources. However, the conclusions drawn are both partial, for it is clear that many issues remain to be resolved, and personal, in that what we are suggesting is to some extent speculative.

There seems little doubt that chemistry, and related, curricula in respect of a model for the triplet relationship must change if chemical education is to be a more successful enterprise than at present. To be meaningfully implemented, a changed curriculum must have direct impact both on what and how students actually learn in the classroom/laboratory and how they subsequently utilise that learning. The history of science education in general is littered with ‘desirable developments’, the significance of which never actually registered with students; a typical example is ‘discovery learning’. A meaningful implementation is one that is understood by all the parties to any change and reflects all aspects of the innovation.

Van den Akker, building on the ideas of Goodlad (1979), has pointed out that the curriculum in any subject takes many forms, namely:

- the *ideal* curriculum: the original vision underlying a curriculum (its basic philosophy, rationale or mission)
- the *formal* curriculum: the vision elaborated in the curriculum document (which has either a prescribed/obligatory or a exemplary/voluntary status)
- the *perceived* curriculum: the curriculum as interpreted by its users (especially the teachers of it)
- the *operational* curriculum: the actual instructional processes taking place in the classroom, as guided by the perceived curriculum (this is often referred to as the curriculum-in-action or the enacted curriculum)
- the *experiential* curriculum: the actual experiences that the students have that are derived from the course as provided
- the *attained* curriculum: the resulting learning displayed by the students at the end of the course (Van Den Akker, 1998, pp. 421–422).

For the subsequent implementation of an *ideal* curriculum to be meaningful, it must be carried through fully to the *attained* curriculum stage with as little ‘slippage’ of philosophy, substance, or process along the way as possible. It is ‘slippage’ that leads to ‘innovation without change’ i.e. to an innovation of little if any impact on student learning and attitudes. The Goodlad/Van den Akker model can be used to discuss the present case to show how an ideal vision of education about the triplet relationship *might* be carried through to the attained curriculum stage. To convert this statement of what *might* be done into a statement of what *can* be done will, it will become evident in what follows, require more research and development.

Whilst some major curriculum developments, such as those funded by the Nuffield Foundation in the 1960s and 1970s in the UK, did carry through, to a fair approximation, all the stages of the Van den Akker model, recent attempts at large-scale curriculum implementation have only weakly been supported in the ways indicated above. We would argue that, given the pivotal importance of a representational triplet in chemical education, a full development programme is urgently needed that has a substantial research underpinning similar to the work presented in this book.

The Ideal Curriculum

There are two higher order questions to be addressed in deciding about the curricular treatment of the triplet relationship. The first is 'why ought students be taught the triplet relationship?' and 'to whom should it be taught?'

To answer the 'why' question, we must first look at the spectrum of reasons why any ideas from chemistry *might* be taught. Roberts (Roberts & Ostman, 1998) identified seven 'emphases' that have been present in the history of the broad sweep of science education in North America. The presence of each of these emphases represents a wish to have content (whether identical, similar or different) treated in a different way, for a different purpose. The balance between the emphases in respect of a particular item of curriculum content that is common to all of them implicitly reflects the significance attached to that content by the stakeholders responsible for its inclusion in the overall curriculum. We discuss the 'chemistry curriculum' as a recognised sector of 'science education' and have placed the seven possible types of emphasis into two groups: *Group A* contains three emphases and is concerned with the student as person, citizen and employee. The *Group B* emphases are to serve the interests of those who will study chemistry or related sciences to an advanced level. This division resembles the distinction made by Roberts (2007, p. 730) between '*scientific literacy*' (which is about 'science-related situations in which considerations other than science have an important place at the table') and '*science literacy*' (which is about 'looking inwards at the canon of natural science and the products and processes of science itself').

Group A contains three emphases:

- **Everyday coping**: Doing so involves making sense of objects and events of obvious everyday importance. This would certainly be included in 'need-to-know chemistry' and also be relevant to 'functional chemistry', the latter being of importance to people in chemistry-based occupations (Aikenhead, 2006). An example is an understanding of the mechanism by which an antibiotic acts, thus justifying the continuation of a course of treatment for as long as directed by a physician.
- **Self-as-explainer**: This involves the process by means of which chemical explanations are produced, and entails a consideration of what influences people's approaches to explaining things and events and of the way the process has, and does, function. This would be of importance to those who deal with 'have-cause-to-know chemistry', experts who deal with the general public on real-life issues

(Aikenhead, 2006). An example, which is obvious given the thrust of this book, is the nature of the macro/submicro relationship and its explanatory value in the practice of chemistry.

- **Chemistry, technology and decisions**: This emphasis is concerned with the way that chemical knowledge is reflected in technological innovations and with the social, political, and economic decisions that such innovations entail. This emphasis would also be part of 'have-cause-to-know chemistry' (Aikenhead, 2006).One example is the chemical basis for recycling and for household waste disposal. Another example is the structure of polymers, this explaining the strength of light-weight materials when used in the clothing and building industries.

There are two emphases that fall within our Group A and which were not included in Roberts' historical description. The first is 'enticed-to-know chemistry', which is of concern to those who work in the media, including the internet, and whose task is to interest the public in science and to spread an awareness of recent exciting developments. An example is the explanation of the chemical basis for stem-cell biology. The second, the oversight of which is rather amazing, is the 'personal curiosity chemistry' wanted by students themselves (Aikenhead, 2006). Examples are provided by those questions having answers based in chemistry which appear in 'The Last Word' column in the weekly *New Scientist* magazine: a collection of questions and answers has been published by O'Hare (2006).

- **Correct explanations**: These are the conclusions so far reached by chemistry that are needed for the citizen to understand how the world-as-experienced works. This emphasis is valued by the general public and is otherwise called 'need-to-know chemistry' (Aikenhead, 2006). An example is an understanding of the mechanism by which a painkiller acts.

  Group B consists of two emphases:
- **Chemistry skill development**: This is the process of the development of chemical knowledge treated as if it involved the acquisition and use of a series of de-contextualised skills. Examples are the development of the skills in working with chemicals of dissolving, reacting, precipitating, filtering, distilling, all of which play key roles in the conduct of chemistry in the laboratory.
- **Structure of chemistry**: This is coming to understand how chemistry functions as an intellectual enterprise. The emphasis is placed by those interested in 'chemistry-as-culture'. An example would be the way that the triplet relationship is used to provide explanations of chemical phenomena.

These two emphases are placed in a curriculum at the behest of academic chemists, education officials, and many chemistry teachers, who wish to ensure that students are equipped to continue with the study of chemistry. These emphases have been collectively called 'wish-they-knew-chemistry' (Aikenhead, 2006; Fensham, 2000).

Roberts (Roberts & Ostman, 1998, pp. 37–38) states that there are two default emphases that do not communicate a clear explicit message about why science is important: ‘Correct Explanations’ and ‘Solid Foundations’. The implicit message conveyed to students by these emphases is ‘master now, question later’. Although such emphases are prominent in many chemistry (indeed, in science generally) curricula, we believe that they are dysfunctional in their impact on the motivation of students to learn chemistry.

The Group A emphases are those that inform the development of ‘chemical literacy’ (DeBoer, 2000) and should be made available to all students (cf. ‘scientific literacy’ – (Roberts, 2007). These emphases all call for an understanding of a macro type of representation, so that learners appreciate what it is when they encounter a ‘chemical phenomenon’ e.g. a solution, a colloid, a precipitate. This understanding would enable students to answer the question ‘what is it?’ and possibly ‘what to do with it: how to act?’ when they encounter such a chemical phenomenon. These emphases also call for an understanding of the submicro type of representation, so that learners can *qualitatively* explain the nature of the macro phenomena that they encounter: and hence be able to answer the question ‘why is it as it is?’ In order to explore these emphases, a chemistry curriculum would need to address a variety of contexts related to the three Group A emphases that have meaning in the ‘everyday’ world. Pilot, Meijer and Bulte (2008) discuss three such contexts: ceramic crockery, gluten-free bread and the bullet-proof vest.

The Group B emphases are to serve the interests of those who will study chemistry or related sciences in greater depth. These students will need an understanding of the macro and submicro types of representation of a more comprehensive type than students learning in Group A curricula. The more comprehensive curricula can be built on the earlier foundations. The students studying a Group B emphasis will also require an understanding of symbolic types of representation so that they can also provide *quantitative* explanations of phenomena. Through the use of the symbolic type they will be able to answer the question ‘how much of it is present?’ in respect of a chemical phenomenon, leading to an understanding of the extent of a chemical reaction and hence to a possible explanations of the reaction mechanisms involved. The traditional contexts of chemistry education, often the contexts in which the ideas were originally discovered / invented, will be adequate if not necessarily inspiring. The use of contemporary ‘authentic research contexts’ is highly desirable here too. Furthermore, for those students who wish to engage in the creative sciences, in engineering/technology, in industrial design, in architecture, a quantitative approach to material science (e.g. strength of fibres) and its precise use is highly important. The choice of contexts should be in accordance with the emphases from Group B.

If this argument, that of a justification for dividing ‘emphases in chemistry education’ into two Groups, has any merit then the major challenge to be faced in the structuring of chemical curricula will be how to deal with the interrelation between macro and submicro types for everybody (Group A), whilst also dealing with a symbolic types with possible future chemistry or chemistry-related specialists (Group B). The realities of educational systems suggest that the Group A emphases be addressed first, so that everybody learns about them, with the Group B emphases coming later and only for those who want to specialise in chemistry.

The Formal Curriculum

Some common themes in recent efforts at curriculum reform emerged in the work of Anderson (1995). As these themes seem to have been at least partially successful in respect of other areas of the science curriculum, they could usefully underlie the formal curriculum requirements in respect of the triplet relationship. These themes value the paying of more attention to:

- the integration of subject content into themes. The overarching notion of 'representation' could serve to facilitate this. For the Group A curriculum, the focus would be on the interrelation between the macro and submicro types, whilst for the Group B curriculum, the focus would be on the triplet relationship in which a symbolic level provides access to quantitative reasoning.
- in-depth treatments of major ideas rather than on isolated facts. For the Group A curriculum, the treatment of the submicro types would be guided by the ideas outlined by Bucat and Mocerino (2008), whilst for the Group B curriculum, the treatment of the symbolic type would be guided by the ideas outlined by Taber (2008).
- linking subject content and the application of those ideas. For both curricula, all content would be linked by the appropriate notions of representation. As has already been remarked, the Meijer, Bulte and Pilot chapter that focuses on 'authentic contexts' has much to commend it.
- developing an understanding of those concepts and the ability to think critically about them for all students. The key to success here would be the extensive use of problem-based learning.

The use of Schwab's idea of the substructures of a discipline, introduced into this book by Van Berkel, Pilot and Bulte, may serve as a framework for the ideal curriculum. However, they take a more practical form when setting out the formal curriculum. Schwab (1964) divided a discipline into three parts for educational purposes – the substantive, the syntactical and the pedagogical. In an actual curriculum, these three are interlocked. However, for the purposes of analysis, taking each in turn:

The Substantive Substructure

This is the conceptual structure that defines the scope of enquiry into a subject. In the case of the Group A curriculum, it would include the natures of the macro type discussed briefly by Gilbert and Treagust (2008b) in the Introduction, of the submicro type discussed by Bucat and Mocerino (2008) and by Davidowitz and Chittleborough (2008). The nature of the symbolic type, which falls within the remit of the Group B curriculum, has been discussed by Taber (2008).

Teaching based on contexts in respect of which these concepts are prominent will serve to link them together. These contexts may therefore be considered, if only partially, as part of the conceptual structure of the subject. In respect of the Group A curriculum, the need for ‘authentic tasks’, i.e. those that are carried out within communities of professional practice and which therefore serve as forums for explicating and linking these concepts together, is stressed by Meijer et al. (2008). The situation regarding the Group B curriculum is as problematic as that for Group A. Whilst the use of contemporary research contexts would perhaps provide some obvious relevance to the learning about the symbolic type of representation, conventional contexts of chemistry may be adequate. The case for ‘inorganic qualitative analysis’ serving as such an authentic task is presented by Tan, Goh, Chia, and Treagust, (2008).

The Syntactical Substructure

This is the framework of methodologies that can be used to conduct legitimate enquiries in a subject, meaning those which lead to the production of acceptable scientific knowledge. The natures of each of the types within the representational triplet and their relationships to each other provide an explanatory framework in respect of all chemical phenomena. The macro and submicro types of representation do so for the Group A curriculum at the desired qualitative level, whilst the addition of the symbolic type completes the scope of chemical explanation in the Group B curriculum.

A core methodology is the capacity to form mental images, or visualisations, of what is happening in the submicro and symbolic types of representation. Indeed, as Justi, Gilbert and Ferreira (2008) have argued, being able to do so fluently, i.e. in a wide range of familiar and unfamiliar contexts, is a measure of methodological competence. This fluency is referred to as *metavisual capability* and involves:

- understanding the conventions for all the modes and sub-modes of representation. For the Group A curriculum, this is all those used of the submicro type, whilst for the Group B curriculum this is all those used of the symbolic type.
- the capacity to mentally ‘translate’ the representation of a given macro phenomenon to and between the submicro and symbolic types of representation. For the Group A curriculum this means being able to do so within and between the macro and submicro types. For the Group B curriculum, metavisual fluency must be expanded to include the symbolic types of representation
- the capacity to construct a representation of a macro-level phenomenon in a submode of the submicro or symbolic types in order to serve a particular purpose. This capacity would form a major theme in the respective curricula.
- the capacity to use such visualisations in order to construct predictions of the behaviour of a phenomenon under varied conditions.
- the capacity to solve novel problems by using analogies to already-known visualisations.

Scheffel, Brockmeier, and Parchmann (2008) have shown how historical material can be used to illustrate the processes by means of which the predictive value of qualitative explanations evolved using ever-changing ideas about the nature of the submicro type. An identical argument applies in respect of quantitative explanations, using ideas about the nature of a symbolic type of representation. Approaches using historical documents do have the potential to show how the scope of visualisation expanded in the evolution of chemical theory.

The Pedagogical Substructure

This is the framework of teaching and learning methods that are used to communicate the substantive and syntactical structure of a subject. This framework has been extensively discussed in this book:

- by Tsaparlis (2008) in respect of the general value of practical experience of phenomena at the macro type. His argument is that such experience is a vital prelude to and part of the learning of both the submicro and symbolic representational types.
- by Tan et al. (2008) who also see practical work as a way of conceptually linking the macro and submicro types using inorganic qualitative analysis.
- by Treagust & Chandrasegaran (2008) who emphasise the importance of relating macro, submicro and symbolic thinking during the actual teaching of lower secondary school practical work.
- by Meijer et al. (2008) who believe that student tasks (including some aspects of practical work) should be in respect of ‘authentic’ tasks set within ‘communities of practice’. Such tasks may be considered as vital for the Group A curriculum and highly desirable for the Group B curriculum.
- by Davidowitz & Chittleborough (2008), by Cheng & Gilbert (2008), and by Justi et al. (2008) who perceive the role of visualisation to play an important role in learning about all aspects of a representative triplet.
- by Scheffel et al. (2008) who advocate participative pedagogies based on the discussion of historical-based materials.
- by Chiu & Wu (2008) who see a major role for computer-based representational systems. Their arguments apply to both types of curricula. Whilst such methodologies play only a limited role in teaching and learning at the moment, that role is likely to expand rapidly in the near future as more and improved software is available at reduced costs. Another factor driving the use of computer-based representational systems is a world-wide shortage of science teachers with a comprehensive understanding of these key chemical ideas.
- by Justi et al. (2008) who discussed the value of a supportive pedagogy for the production of models that entail representation at both the submicro and symbolic types. A suitable pedagogy is one that will: recognise the salience of students’ prior ideas about representation; be based on practical experience as a foundation for the production of models; encourage the expression and supportively critical discussion of those models; and recognise the value of teachers’ questioning in the evolution of models with explanatory value.

‘Action research’ is an approach that can be applied to designing the formal curriculum that has much to commend it if impracticalities and content overloading are to be avoided and intellectual coherence enhanced. In essence, the approach consists of the following stages: the identification of practical problems of teaching and learning in classrooms; the development of possible solutions to those problems; their implementation in classrooms; the evaluation of the educational value of the changes made. The cycle may be repeated until a satisfactory outcome is achieved. Ferk Savec, Sajovic, & Grm (2008) report the success of a variation of this general approach. In their case study, a group of chemistry teachers collectively identified problems with the triplet relationship at national level and then designed materials and teaching approaches to address them. The individual teachers then implemented the solutions in their respective classrooms, pooling their experience to produce materials/pedagogy capable of widespread adoption.

The Perceived Curriculum

The design of the formal curriculum usually receives the particularly close attention of all the stakeholders, especially teachers, who have been involved in producing the ideal curriculum. Assuming that this design is thought through carefully, from both a theoretical and practical viewpoint, the first major step to implementation, if it is a radically new venture, or in evolution, if it has developed from an existing curriculum, is to make sure that all the teachers who may use it know *what the curriculum is and what it is intended to achieve.* This step entails universal teacher education, both for those who are in pre-service training and those who already are employed as a teacher: taken together, these two overlapping phases are usually called ‘teacher professional development’

Although there are major differences between national educational systems, some broad guidelines for successful science teacher professional development, culled from a review of recent curriculum development projects (Black & Atkin, 1996, pp. 146–147; Van Den Akker, 1998, pp. 443–444) can be applied to a revised curricular provision in respect of the triplet relationship. The intention must be that the perception of new curricular provision by all teachers becomes congruent with the intentions, content, and processes, of the formal curriculum. The guidelines suggest that

1. There should be a general acknowledgement that there is a problem in respect of current curricular provision. Change begins with ‘disequilibrium’ – a realisation that current practices cannot achieve desired educational goals. In the case of the triplet relationship this would involve chemistry teachers becoming explicitly aware of the outcomes of research into students’ problems with the triplet relationship (see the Introduction to this book) and into students’ dissatisfaction with the present chemistry curriculum (Osborne & Collins, 2000). This might

be done through a formal lecture, the organisation of regional and/or national debates on the contents of the chemistry curriculum and/or by the provision of e-learning materials.

2. Exposure to other ideas, resources and opportunities broadens teachers' awareness of possibilities for change and fosters a sense that alternatives are available. Teachers would make use, initially on a small scale, of classroom materials developed especially to meet the new approaches to models of the triplet relationship (see especially: Tsaparlis, 2008; Tan et al., 2008; Meijer et al., 2008; Davidowitz & Chittleborough, 2008; Justi et al., 2008; Treagust & Chandrasegaran, 2008). This awareness of alternative resources implies either that such materials are prepared beforehand (Van Berkel, Pilot, & Bulte, 2008) or that the teachers themselves prepare the materials by an 'action research' approach (Ferk Savec et al., 2008).
3. Proof that the new approaches 'work' under normal classroom conditions gives moral support to teachers and challenges them to change their own perceptions of teaching, learning and the curriculum. The results of the evaluation of formal trials of new materials and approaches about the triplet relationship should be made available to the teachers. One effective way to do so is to organise matters such that teachers who made trial use of the materials share their experiences with others (Ferk Savec et al., 2008).
4. Opportunities for teachers to observe new teaching and learning techniques in real classroom situations, for example, by watching demonstrations, and reflecting on the enactment of the new ideas, deepens their understanding of what is involved. Such modelling strengthens the proof of existence of the new approach. Also, visits to observe the materials about a triplet relationship being trailed by experienced teachers in their schools would allow important pragmatic questions to be asked.
5. Personal support (both knowledgeable and close at hand) is essential for facing the risks associated with an innovation and overcomes the usual performance decline of activities during its initial implementation. Teaming up teachers for mutual support is valuable. The use of trial teachers as mentors to visit schools where other teachers begin to use the materials in order to supportively critique emergent practice would meet this point (Ferk et al., 2008)
6. The encouragement of experimentation throughout a whole–school environment or in a peer-group network reduces perceived risks. Before any substantial change to normal practice is made in a school in respect of a triplet relationship, all the teachers of chemistry and their heads of department and administrators should be aware of what is to happen and be broadly supportive of it.
7. The experimental introduction of an innovation should be intertwined with opportunities for systematic reflection on it by the chemistry teachers, for this will increase their understanding of the innovation and their competence in teaching it. The process of introduction of new curricula in respect of a triplet relationship must take place over an extended period of time, with all the teachers involved having opportunities to meet, to compare experiences, to identify current successes and future challenges.

What should *not* be done, because it is so ineffective and which is *still* widely done because it is considered by administrators to be ‘economically efficient’, is to give teachers two or three half-day lectures on the innovation and then provide them with no on-site and sensitive, interactive, support to relate it to the particular circumstances in their own schools. Changing the curriculum, teaching, and learning, in respect of the triplet relationship requires the above guidelines to be clearly born in mind if the formal and perceived curricula are to be mutually congruent.

The Operational Curriculum

During and after programmes of professional development and curriculum evolution, any innovatory curriculum in the triplet relationship will be put into operation in classrooms. As the purpose of teaching is to promote learning, what should be done in classrooms to maximise the desired learning? Black & Atkin (1996) have summarised the ‘traditional’ assumptions about learning that have proved so unsatisfactory in the past. These are that

- ‘knowing that’ must come before ‘knowing how’
- the effective sequence of learning is first to receive and memorise, then to use in routine exercises so as to develop familiarity and understanding, before attempting to apply.
- it is better to teach at the abstract level first and then leave the business of applications in many different contexts to a later stage.
- motivation can be achieved by external pressure on the learner, not by change in the mode of learning or the presentation of the subject.
- difficulty of failure of learning by the traditional route arises from the innate lack of ability, or inadequate effort, rather than from any mismatch between the teacher’s preferred learning style and the student’s. (Black & Atkin, 1996, p. 62)

These unsatisfactory past experiences suggest new and different approaches to teaching that can improve the quality learning about the triplet relationship in the future. Taking each of these in turn, ideas from the chapters of this book are identified as contributing to improved practice. Greater success should result from:

1. Teaching the significance and value of the triplet relationship in facilitating the explanation of chemical phenomena *before* a treatment of the details of each type and their practical use. This can be provided by the greater use of the ‘pedagogical elements’ associated with a modelling approach to teaching (Justi et al., 2008) that give more emphasis to: students having relevant empirical experience at the time that theory is being introduced; teachers engaging more frequently in the questioning of students’ thinking; opportunities for the production of explanations by students; the prior identification of students’ existing conceptual understanding; and the provision of more opportunities for students to express and discuss their explanatory ideas.

2. The extensive use of the triplet relationship during the learning of detailed information. Tan et al. (2008) provide an example of such a detailed teaching scheme, in this case in relation to inorganic qualitative analysis. Treagust and Chandrasegaran (2008) provide another example of a teaching scheme in lower secondary chemistry practical work. Davidowitz and Chittleborough (2008) demonstrate how diagrams can be used to represent complex macro systems in the submicro types.
3. The use the triplet relationship from the outset of teaching in a range of contexts will enable abstract principles to emerge as unifying explanations in these contexts. The use of multiple contexts has been advocated, as has the use of meso-level representations in legitimating the learning of relevant concepts that are situated within such contexts, by Meijer et al. (2008).
4. Teaching techniques should be used which actively engage the interest and involvement of the learner. The importance of clarity of language has been stressed by Bucat and Mocerino (2008). The use of specifically designed materials to teach about diagrams and their use has been discussed and their use illustrated by Davidowitz and Chittleborough (2008). The value of historical materials within a pedagogical framework has been examined by Scheffel et al. (2008) as has the use of multimedia in a range of software programmes by Chiu and Wu (2008).
5. Teachers should be aware of the learning styles of both themselves and their students, being able to accommodate differences between the two. The use and value of different schemes of work involving context-based courses, demonstration lectures and cooperative learning have been provided by Tsaparlis (2008).

With the operational curriculum in place as the appropriate teaching provision, the next consideration is to ensure that what the students actually experience is what the teacher (and the ideal and formal curriculum!) intended.

The Experienced Curriculum

It is important that the activities, especially the modes of thought, in which students are engaged during the introduction of the new curriculum are monitored to ensure that the intentions of the ideal curriculum are carried through into the classroom and laboratory. Such an evaluation should ensure that

a. The tasks in which the students engage are as 'authentic' as possible This will ensure that the use that students make of a representational triplet is as close as is possible to that made by practicing professionals (Meijer et al., 2008);
b. Multimedia are used to best effect. The representational conventions used must match students' preferred learning styles and teachers must provide prompt and appropriate feedback on what is done and learnt (Chiu & Wu, 2008);
c. Students appreciate the significance of parallels between the historical development of knowledge and their own understanding. The statement that 'ontogeny recapitulates phylogeny' is only a metaphor drawing on the historical

development of ideas and is not a literal statement of what occurs during learning. However, knowledge of the historical development of concepts can help the teacher to recognise pitfalls in student conceptualisations and hence have a better understanding of what aspects to emphasise in future teaching (Scheffel et al., 2008; Tsaparlis, 2008);

d. Students' response to teaching programmes built around practical work is what was intended by the originators (Treagust & Chandrasegaran, 2008). This outcome is most likely to occur if the originators of the programmes are clear and overt about their intentions and if students are explicitly told about those intentions;
e. Students get extensive experience in using the sub-modes of a submicro type (Bucat & Mocerino, 2008), especially those associated with diagrams (Davidowitz & Chittleborough, 2008), and, in the relevant curriculum, a symbolic type (Taber, 2008). This repeated experience will build, clarify and consolidate links between these three types. The complexities of the demands that these processes make should not be underestimated by teachers of chemistry who should remind themselves that they hold their position because (it is fervently to be hoped!) they understand the natures of and the relationships between the three types;
f. Students' appreciate the purposes of the various types of practical work in respect of learning about the triplet relationship (Tsaparlis, 2008). Again, the relationship between the nature of the thinking involved in the practical work and the use of the triplet relationship should be made explicit to students as illustrated in the chapter by Treagust & Chandrasegaran (2008);
g. The curriculum emphases being addressed in any unit of work must be known to the students. The key issue here is that students must both know and accept why they are learning a particular curriculum. This will help them see how the triplet relationship contributes to an appropriate understanding of those emphases (Van Berkel et al., 2008). Perhaps the key issue here is that students both know and accept *why* they are learning a particular curriculum.

If the intentions of the formal curriculum, as appreciated by the teachers, 'translated' into the realities of the everyday classroom/laboratory, are evident in the work of the students, the process of successful implementation may be said to be nearly complete.

The Attained Curriculum

The intentions of any new curriculum can only be said to have been realised when it is demonstrated, through assessment, that the students' learning was what was intended. In this case, it means that

- Attainment in respect of each component of practical work, which is so vital in linking the macro level to the submicro and symbolic types, must be assessed (Tsaparlis, 2008). This does mean that practical work must have been subjected to an analysis such that it *can* be comprehensively assessed. Moreover, appropriate instruments for assessing each component of practical work in respect of the attainment and use of the three types of representation must be available (Treagust & Chandrasegaran, 2008);

- understanding all the varieties of the submicro types (Bucat & Mocerino, 2008), especially of diagrams (Davidowitz & Chittleborough, 2008), and of the varieties of symbolic representation (Taber, 2008), must be demonstrated. This understanding must be attained not only in respect of practical work (see above) but also in other aspects of students' work in chemistry such as in problem-solving;
- the assessment of the attainment/use of metavisualisation (Justi et al., 2008) can involve the application of psychometric tests (Gilbert, 2005) and/or diagnostic tests (Chandrasegaran, Treagust & Mocerino, 1997). Moreover, such tests must be applicable to the aims addressed and the content taught in the full range of 'curriculum emphases' (Van Berkel et al., 2008);
- a wide range of 'communities of practice' must be represented in the 'authentic tasks' engaged in by the students, for these are the contexts in which assessment is set (Meijer et al., 2008);
- multimedia may be used as vehicles for the presentation of assessment instruments (Chiu & Wu, 2008).

What Research and Development Is Now Needed?

This book is an advocacy for using a consideration of the triplet relationship as the basis for curricula in chemical education. However, there has been a major issue in doing so. This concerns terminology: should the word 'type' be used to treat macro, submicro, symbolic representations as ontologically separate, an approach which would leave their cognitive status to one side, or should the word 'level' be used, implying a cognitive hierarchy between them? We have felt that the use of 'type' enabled progress to be made more easily is discussing macro, submicro and symbolic representations *separately*. However, the word 'level' is more useful when discussing the cognitive relationship between all three. Moreover, the two approaches must be brought together.

The problem in doing so is that the term 'level' can be used in two different ways. Firstly, 'level' can have the meaning of 'scale/size/measure'. This meaning comes to the fore when, for example, submicro representations are described as 'models [that] involve 'entities' that are too small to be seen using (conventional) microscopes' (Gilbert & Treagust, 2008a). This meaning can be invoked by the introduction into the discussion of intermediate or 'meso' levels, as has been illustrated by Meijer et al. (2008). Doing so enables the aims of chemistry education to be broadened in relation to technology and to the other sciences, for intermediate representations of fibres, crystalline, amorphous structures, DNA strings, G – T – A – C triplet codes for genes, etc. can then be readily used as models for explaining and predicting phenomena.

A second meaning of ‘level’ implies a change from concrete familiar language to abstract specialised chemical language expressed in a very reduced form of a symbol or an image (Justi et al., 2008). To give two examples: O_2 representing a molecule of oxygen that consists of two atoms of oxygen atoms connected by a chemical bond; CGCGAATTCGCG represents a base pair sequence in DNA. Behind the symbols, there lies a whole world of interconnected concepts, which have gradually to be learned as ‘the grammar’ of chemistry. The usefulness of this abstract mode of representation has been developed and used by the community of practicing scientists over the centuries, for it enables them to communicate using short, reduced, forms of precise specialised language.

We can attempt to reconcile the ideas of ‘type’ and the two meanings of ‘level’. In Fig. 14.1 the triplet relationship between the macro, micro and symbolic ‘types’ is represented as ‘levels’ in the form of a triangle. The distinction between the two different meanings of ‘level’ is given in the picture on the right-hand. When relating phenomena at a macro scale to representations of models at different scales, millimetre, to micrometre to nanometre (see for example Meijer et al., 2008), the necessity exists to use more and more specialised language using symbols with letters and images. The learning of this specialised language can only become meaningful when embedded in the students’ experiences with real phenomena, sequencing from concrete to abstract, using photographs and visuals, and invoking the use of metavisual competencies. For the Group A curricula there is no need for a very detailed use of chemical language as compared with Group B curricula, since these types of curricula would be concerned with different degrees of ‘fluency’/‘literacy’. As we have stated, a systematic and well-established curriculum development process should be followed for which the Goodlad/Van den Akker model is a good basis, in

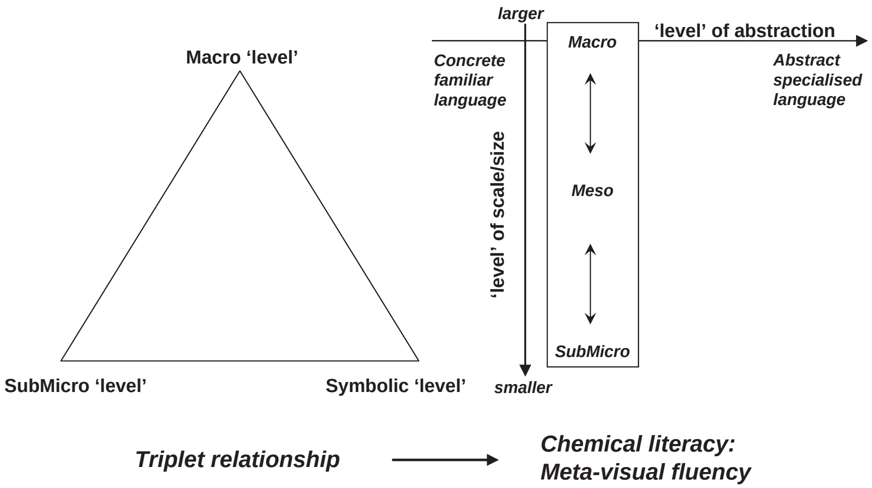


Fig. 14.1 From the model of the triplet relationship to metavisual fluency: flexibility in relating the different representations to scale, and fluent use of special chemical language with an appropriate ‘grammar’

order to avoid the intent and impact of proposed changes/innovations being eroded in the course of moving from the ‘ideal’ curriculum to the ‘learned curriculum’.

Inevitably, this book – especially this chapter – leaves several major questions to be answered by further work:

- what is an appropriate model for chemical education using the triplet relationship as a starting point (Fig. 14.1)
- what are the precise requirements in respect of this model for Group A and Group B curricula?
- what, in detail, should be taught about the macro, meso and submicro/symbolic levels and how should the sequence of those ideas be progressed during the years of schooling using appropriate exemplar contexts?
- what, in detail, should be taught about the specialised chemical language of symbols and images?
- what would be treatment of such language in the two curricular types (A and B) and how should the sequence of those ideas be progressed during the years of schooling to achieve metavisual fluency?
- what are the full implications of having such a complete ‘metavisual capability’?
- how can the ability to think ‘up’ and ‘down’ between levels of scale and between everyday and specialised language be fostered?
- how can the various aspects of metavisual fluency be best assessed?

The authors who have contributed to this book have already considered some of these issues, but usually at the scale of a class or classes in one or more schools or universities, rather than within an educational jurisdiction. A larger-scale address to this set of endemic problems is called for. Clearly, there is much to do.

Acknowledgments We are grateful to Keith Taber, Georgios Tsaparlis, and most especially to Albert Pilot and Astrid Bulte for most helpful comments and suggestions on an earlier version of this chapter.

Literature About Students’ Conceptions

Aikenhead, G. S. (2006). *Science education for everyday life*. New York: Teachers College Press.

Anderson, R. D. (1995). Curriculum reform: dilemmas and promise. *Phi Delta Kappan, 77*(1), 33–36.

Black, P., & Atkin, J. M. (Eds.). (1996). *Changing the subject*. London: Routledge.

Bucat, B., & Mocerino, M. (2008). Learning at the sub-micro level: Structural representations. In J. K. Gilbert, & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Chandrasegaran, A., Treagust, D. F., Mocerino, M. (1997). The development of a two-tier multiple-choice diagnostic instrument for evaluating secondary school pupils’ ability to describe and explain chemical reactions using multiple levels of representation. *Chemical Education Research and Practice, 8*(3), 293–207.

Cheng, M., & Gilbert, J. K. (2008). Towards a better utilisation of diagrams in research into the use of representations in chemical education. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Chiu, M.-H., & Wu, H.-K. (2008). The roles of multimedia in the teaching and learning of the triplet relationship. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Davidowitz, B., & Chittleborough, G. (2008). Linking the sub-micro and symbolic levels: Diagrams. In J. K. Gilbert & D. F. Treagust (Eds.), *Mutliple representations in chemical education*. Dordrecht: Springer.

DeBoer, G. E. (2000). Scientific literacy: Another look at its historical and contemporary meanings and its relationship to science education reform. *Journal of Research in Science Teaching, 37*(6), 582–601.

Fensham, P. J. (2000). Providing suitable content in the ‘science for all’ curriculum. In R. Millar, J. Leach, & J. Osborne (Eds.), *Improving science education: The contributions of research* (pp. 147–164). Buckingham, UK: Open University Press.

Ferk Savec, V., Sajovic, I., & Grm, K. S. W. (2008). Action research to promote the formation of linkages by chemistry students between the macro, sub-micro, and symbolic representation levels. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Gilbert, J. K. (2005). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education*. Dordrecht: Springer.

Gilbert, J. K., & Treagust, D. F. (2008a). The complex relationships between the macro / sub-micro /symbolic levels of representation in chemical education: An Introduction. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Goodlad, J. (1979). *Curriculum enquiry: The study of curriculum practice*. New York: McGraw-Hill.

Justi, R., Gilbert, J. K., & Ferreira, P. F. M. (2008). The application of a ‘model of modelling’ to illustrate the importance of metavisualization in respect of the three levels of representation. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Meijer, M., Bulte, A. M., & Pilot, A. (2008). Structure-property relations between macro and submicro representations: Relevant meso-levels in authentic tasks. In J. Gilbert, K. & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

O’Hare, M. (Ed.). (2006). *Why don’ t penguins’ feet freeze?* London: Profile Books.

Osborne, J., & Collins, S. (2000). *Pupils’ and parents views of the school science curriculum*. London: King’s College London.

Roberts, D. A. (2007). Scientific Literacy / Science Literacy. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research in science education* (pp. 729–780). Mahwah: Erlbaum.

Roberts, D. A., & Ostman, L. (1998). Analysing school science courses: The concept of companion meaning. In D. A. Roberts & L. Ostman (Eds.), *Problems of meaning in science curriculum* (pp. 5–12). New York: Teachers College Press.

Scheffel, L., Brockmeier, W., & Parchmann, I. (2008). Historical material in micro-macro thinking: Conceptual change in chemistry education and in the history of chemistry. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Schwab, J. J. (1964). The structure of the natural sciences. In G. W. Ford & L. Pugno (Eds.), *The structure of knowledge and the curriculum* (pp. 1–31). Chicago: Rand McNally.

Taber, K. (2008). Learning at the symbolic level. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Tan, K. C. D., Goh, N. K., Chia, L. S., & Treagust, D. F. (2008). Linking the macroscopic, submicroscopic and symbolic levels: The use of inorganic qualitative analysis. In J. Gilbert, K. & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Treagust, D. F., & Chandrasegaran, A. L. (2008). The efficacy of an alternative instructional program designed to enhance secondary students’ competence in the triplet relationalship. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Tsaparlis, G. (2008). Learning at the macro-level: The role of practical work. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Van Berkel, B., Pilot, A., & Bulte, A. M. (2008). Micro-macro thinking in chemical education: Why and how to escape. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education*. Dordrecht: Springer.

Van Den Akker, J. (1998). The science curriculum: between ideals and outcomes. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (Vol. 1, pp. 421–448). Dordrecht: Kluwer.

About the Authors

Berry van Berkel is currently involved as adviser and developer in a major science curriculum development project based at an educational publishing firm in the Netherlands. He is further employed at a printing firm overseeing systems of quality, environmental and safety assurance. He obtained his M. Phil. in History and Philosophy of Science at the University of Amsterdam. Following his M. Ed. in Chemistry at the University of Utrecht, he taught Chemistry in secondary schools, and provided public understanding of science at the Utrecht University Science Museum. Subsequently he worked as a researcher in chemical education and published his Ph.D. thesis on The Structure of Current School Chemistry, A Quest for Conditions of Escape (2005) at the Centre for Science and Mathematics Education, Utrecht University. His publications deal with the way the traditional chemistry curriculum act as an internal constraint on the teaching, development as well as on research of innovative STS- or HPS-based chemistry curricula. His other research interests are the foundations of science education as a piecemeal social “engineering” science, and the perspectives and/or “logics” of science operative in different practices of science and science education.

Wiebke Brockmeier studied Chemistry and English for secondary education in Oldenburg from 2002 to 2007. In 2007, she finished her examination with a thesis on children’s ideas about models of metals and ionic structures. Recently, Wiebke Brockmeier completed her teacher’s training in Celle.

Bob Bucat is an Associate Professor in Chemistry at the University of Western Australia. His particular interests are in the non-linear complexity of learning chemistry, visualisation to aid understanding, pedagogical content knowledge, the tensions between accuracy and learnability, the presentation of chemistry as a modelling science, and the precision of instructional language. Bob has been a titular member of the Committee on Chemical Education of IUPAC, a winner of the Distinguished Teacher Award at his university, and a recipient of the Medal of the Chemical Education Division of the Royal Australian Chemical Institute. He is a co-editor of the Australian Journal of Education in Chemistry.

Astrid M.W. Bulte is a researcher in science education, being since 1999 connected to the Freudenthal Institute for Science and Mathematics Education at Utrecht University, The Netherlands. In her current position she focuses her research on the development and evaluation of authentic practice-based science units for secondary education. She contributes to the education of student – science teachers, teaching students how to communicate science issues. She takes a leading position in national curriculum developments. After she obtained her Master degree in Chemical Engineering Science in 1989, she completed her doctoral thesis in 1994 in the same subject at the same university. From 1994 till 1999, she was a teacher of physics and chemistry in secondary education.

A.L. Chandrasegaran is a post-doctoral researcher at the Science and Mathematics Education Centre, Curtin University of Technology, Australia. He holds a BSc (Hons) (Canterbury, NZ), a MSc(ScEd) (Curtin), a PhD (Curtin), and a Teachers' College Diploma (Christchurch, NZ). For most of his career he has taught secondary school chemistry in Malaysia, Singapore and Perth, including 12 years serving as the principal of a large secondary school in Johor, Malaysia.

Maurice Cheng is a Teaching Consultant in the Faculty of Education, The University of Hong Kong. His teaching areas include science and chemistry education, and learning psychology. He has taught in secondary school, and serves on the official curriculum and assessment committees (science and chemistry subjects) of Hong Kong. He holds B.Pharm., PGDE (chemistry), MEd and is now undertaking PhD study in The University of Reading, UK.

Lian Sai Chia is Associate Professor Fellow at the National Institute of Education, Singapore. He obtained a BSc (Nanyang University, Singapore), an MSc and a PhD (both from University of British Columbia, Canada), all in Chemistry, as well as a Certificate in Education (Teachers' Training College, Singapore) and an MA (Michigan State University, USA). He taught chemistry in secondary schools for about 8 years before joining the present institute. His research interests include chemistry of bioactive compounds, sonochemistry, environmental chemistry, and learning strategies/instructional design in chemistry/science.

Gail Chittleborough is a Lecturer in Science Education at Deakin University, Victoria Australia, working with pre-service primary, secondary science and chemistry teachers. Gail studied Science, majoring in Chemistry and Education at Macquarie University in New South Wales and worked as a Science and Chemistry teacher in Australia, PNG and UK for over a decade. Gail studied Computer Education at Melbourne University before working on an Australian Research Council study into the use of models and modelling in secondary science education. Gail completed her doctoral studies into the role of teaching models and chemical representations in developing students' mental models of chemical phenomena at Curtin University, Perth Western Australia.

Mei-Hung Chiu is Professor of Science Education at The National Taiwan Normal University (NTNU) and has been Guest Editor for a Special Issue of the International Journal of Science Education. She has a BS in chemistry (NTNU), an Ed. M. in Technology in Education, and an Ed. D. in Human Development and Psychology from Harvard University. She taught as a physical science and chemistry teacher in secondary schools for 3 years before serving as a science education researcher and professor at university level. She has published on students' mental models, conceptual change, and analogies.

Bette Davidowitz is an Associate Professor at the University of Cape Town in South Africa and holds a BSc Hons, MSc and PhD (UCT) all in chemistry. She has worked as a scientific officer in the Chemistry Department and was responsible for running the senior undergraduate laboratories. During this time she became interested in research in education in chemistry. She currently holds a lectureship in chemistry where her main duties are teaching under-prepared students registered for the access course. Her research focuses on improving teaching and learning in chemistry both in the classroom and the laboratory. In 2004 she was the recipient of a Distinguished Teacher Award at UCT and the South African Chemical Institute Education medal.

Poliana F.M. Ferreira is a doctorate student in Education at the Federal University of Minas Gerais (UFMG), Brazil. She has a chemistry teacher qualification and a master's degree in Education. She taught chemistry in secondary schools in Brazil. She has also been a lecturer in a chemistry teacher training course at UFMG. Her research interest is in modelling-based teaching and skills assessment.

John K. Gilbert is Professor Emeritus at The University of Reading, Visiting Professor at King's College, London, and Editor-in-Chief of the International Journal of Science Education. He took a BSc (Leicester), a DPhil (Sussex), and a Postgraduate Certificate in Education (London), all in chemistry. He then taught chemistry in secondary (high) schools before moving into science education research at both school and university level. His early work on students' alternative conceptions has evolved into a focus on models and modelling. In 2001 he was the recipient of the award for 'Distinguished Contributions to Science Education through Research' from the USA-based National Association for Research in Science Teaching.

Ngoh Khang Goh is Associate Professor at the National Institute of Education, Nanyang Technological University, Singapore. He obtained his first degree in Chemistry from Nanyang University, Singapore, in 1964. He was then awarded a PSC Overseas Scholarship to pursue his postgraduate studies in Germany, at the University of Muenster, under the ”German Academic Exchange Service” scheme, and completed his studies with both First Class Master and Doctorate degrees. He was the Head of the Chemistry Division (1991 to 2000) and the Deputy Head of the Science and Technology Education Academic Group (2000 to 2004) in the present institute. His research interests include instructional design in chemistry/science, process skills learning, herbal chemistry, environmental chemistry and materials science.

Katarina Senta Wissiak Grm is an Assistant Professor and Researcher in chemical education at the University of Ljubljana, Slovenia. She took a BSc, MSc and a PhD in chemistry, all at the University of Ljubljana. She taught chemistry in secondary (high) schools, before moving into both chemical and chemical education research. Her chemical research has been on the biodegradation and photolysis of organic pollutants in the atmosphere. Her current chemical education research interest is in evaluation of methods for teaching and learning science, including associated teaching material.

Alex Johnstone is an Emeritus Professor of Science Education and was a Professor in Inorganic Chemistry at the University of Glasgow. He graduated with the degrees of BSc (Edinburgh), PhD (Glasgow) and was also awarded the Postgraduate Certificate in Education (Edinburgh). He is a Fellow of the Royal Society of Chemistry (London) and has been the President of its Education Division. His research in the cognitive aspects of Science Education has been recognised by various awards: Nyholm Medal (RSC London), Mellor Medal (University of New South Wales), Illuminati Medal (Italian Chemical Society), Brasted Medal (American Chemical Society), Titular Verhaegen Memorial Chair (Limburg, Belgium), Federation of European Chemical Societies Lectureship (Budapest), Galen 2000 Lectureship (Dublin) and in March 2009 he will receive the American Chemical Society's Award for Achievement in Research for the Teaching and Learning of Chemistry.

Rosária Justi is an associate professor in chemical education both in the Department of Chemistry and in the post-graduate programme in Education at the Federal University of Minas Gerais (UFMG) in Brazil. She has a bachelor's degree in Chemistry, a master's in Education, and a PhD in science education. She has taught chemistry in secondary schools in Brazil. Her current main research interest is in modelling-based teaching.

Marijn R. Meijer is a part time PhD student at the Freudenthal Institute for Science and Mathematics Education at Utrecht University, The Netherlands. The object of his research is macro–micro thinking using structure–property relations. He took a MSc in Chemical Engineering Science and a Postgraduate Certificate in Education in Chemistry and The Science of Public Understanding at The University of Twente. He is a teacher in both subjects for 11 years in secondary (high) school. He participates in several innovative projects related to recent developments on the chemistry curriculum in The Netherlands.

Mauro Mocerino is an Associate Professor in the Department of Applied Chemistry at Curtin University of Technology. He obtained his BSc (Hons), Dip. Ed. and PhD from the University of Western Australia and has had post-doctoral appointments at the Victorian College of Pharmacy and at UWA. He is a Co-editor of the Australian Journal of Education in Chemistry, was Chair of the Chemical Education Division of the Royal Australian Chemical Institute, and the first year chemistry coordinator at Curtin. He has a particular interest in improving the understanding of how students learn chemistry and what can be done to improve their learning. He also has over 20 years experience in organic chemistry.

Ilka Parchmann is a professor of chemistry education at the University of Oldenburg and the speaker of the Graduate programme “ProDid” on Educational Reconstruction. She has a degree as a secondary school teacher and a degree in chemistry education. Before going to Oldenburg, she was working at the Leibniz-Institute for Science Education (IPN) in Kiel. Her main fields of interest in research and development are context-based learning (“Chemie im Kontext”), particularly regarding the development and application of interest and conceptual understanding, and the design and investigation of implementation and teacher training programmes, both in-service and pre-service. Besides, she is coordinating an in-service-training centre for chemistry teachers and a learning laboratory (“CHEMOL”) for primary school children and teachers. She has also been advising the development of the German National Standards for Science Education in chemistry and of several state syllabuses.

Albert Pilot studied Chemistry at Utrecht University in The Netherlands, with a major in analytical chemistry and a minor in educational research. His PhD was in 1980 on learning problem solving in science at the University of Twente. In 1996 he was appointed as full professor of curriculum development in IVLOS Institute of Education at Utrecht University and in 1998 also as professor of Chemistry Education in the Department of Chemistry of that university. His research in Chemistry Education is concentrated in the field of curriculum development, context-based education and professional development of teachers.

Irena Sajovic works partly as a Researcher in Chemical Education at the University of Ljubljana, Slovenia. She took a BSc and MSc in chemical education, all at the University of Ljubljana. Her current research interest is in the evaluation of methods for teaching and learning science, including associated teaching materials.

Vesna Ferk Savec is an Assistant Professor and Researcher in chemical education at the University of Ljubljana, Slovenia. She took a BSc and MSc in chemistry and a Ph.D. in chemical education, all at the University of Ljubljana. Her current research interests are in the evaluation of methods for teaching and learning science, including the usefulness of help-tools and associated teaching materials.

Lars Scheffel studied biology and chemistry for higher education at the University of Kiel, Germany. After his examination in 2005, he started his PhD project at the University of Oldenburg in Chemistry Education under the supervision of Prof. Ilka Parchmann. As a member of the Graduate school “Educational Reconstruction”, he is mostly interested in students' conceptions, concept development and historical dimensions in teaching and learning.

Keith S. Taber is Reader in Science Education at the University of Cambridge. He read for a BSc in Chemistry (Nottingham) before taking the Post Graduate Certificate in Education in Chemistry and Physics. He taught science in comprehensive schools and in further education, whilst studying for a Diploma, MSc and PhD (Roehampton/Surrey) in science education. He has been a Teaching Fellow of the Royal Society of Chemistry. He teaches graduate students in education, some preparing to be teachers, some undertaking practitioner research as teachers, and others training to become educational researchers. His main research interests relate to cognitive and conceptual aspects of learning in science.

Kim Chwee Daniel Tan is Associate Professor at the National Institute of Education, Nanyang Technological University, Singapore. He obtained his BSc (Hons) and Diploma in Education from the National University of Singapore, and MSc and PhD from Curtin University of Technology. He taught chemistry in secondary school for 8 years before moving on to teacher education at the National Institute of Education. His research interests include the development of diagnostic instruments to determine students' understanding of chemistry, the use of representations in chemistry, the science curriculum, practical work and use of information and communication technology in the learning of science.

David F. Treagust is Professor of Science Education at Curtin University in Perth, Western Australia and teaches courses in campus-based and international programs related to teaching and learning science. He taught secondary science for 10 years in schools in England and in Australia prior to working in universities in the USA and Australia. His research interests are related to understanding students' ideas about science concepts, and how these ideas contribute to conceptual change and can be used to enhance the design of curricula and teachers' classroom practice. David was President of the National Association for Research in Science Teaching (NARST, USA; 1999–2001), is currently Managing Director of the Australasian Science Education Research Association, and was the 2006 recipient of NARST's Distinguished Contributions to Science Education through Research Award.

Georgios Tsaparlis is Associate Professor of Science Education at the University of Ioannina, Greece, and founder and currently Co-Editor of *Chemistry Education Research and Practice*. He holds a chemistry degree (University of Athens), and an MSc and a PhD in theoretical chemistry/chemical physics (University of East Anglia). He has taught and is teaching physical chemistry courses at the University of Ioannina, as well as science/chemistry education courses at in-service teacher seminars and at many Greek universities both at undergraduate and graduate level. He has published extensively in science education, his research focus being on problem solving and the role of cognitive factors (including the application of complexity theory), on quantum chemistry concepts, and on teaching methods.

Hsin-Kai Wu is associate professor at the National Taiwan Normal University. She has a MS in organic chemistry and received her PhD degree in science education from the University of Michigan. She has published journal articles on chemistry visualization, scientific inscriptions, learning technologies and inquiry learning in leading journals of science education. She serves on the Editorial Board of the journal Science Education and is a Research Consulting Editor of the journal Educational Technology Research and Development. In 2003, she was the recipient of the Outstanding Dissertation Award from the USA-based National Association for Research in Science Teaching. Her research work was also recognized by the Wu Da-Yu Memorial Award given by the National Science Council from Taiwan in 2004.

Author Index

Subject Index