Chapter 8
Linking the Macroscopic and Sub-microscopic Levels: Diagrams

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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

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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

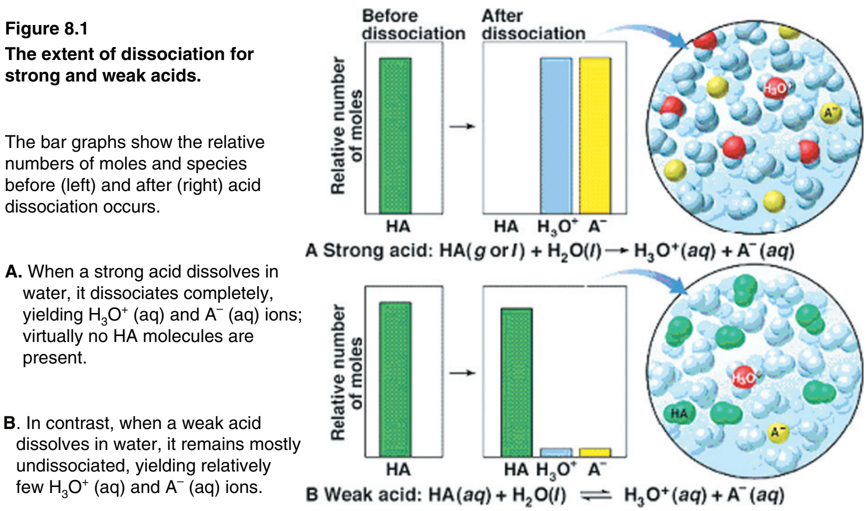


Fig. 8.1 Dissociation of strong and weak acids (from M. S. Silberberg, Chemistry: The molecular nature of matter and change, 3rd ed., McGraw Hill, 2003, p. 760, reproduced with permission of The McGraw-Hill Companies)

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

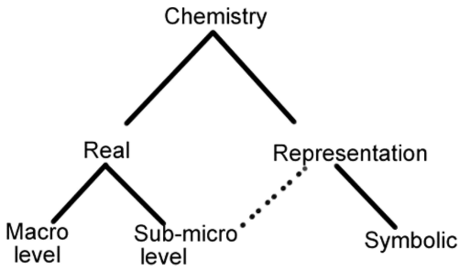


Fig. 8.2 The relationship between the three levels of chemical representations and real and represented chemical data

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

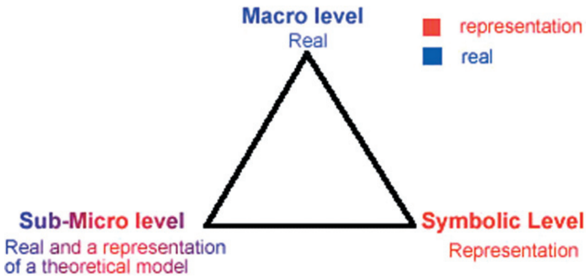


Fig. 8.3 The reality or representational status of the three levels of chemical representation of matter

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).

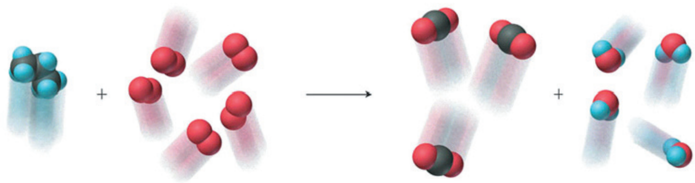
According to Hinton and Nakhleh (1999), macro, sub-micro and symbolic representations are each appropriate tools to illustrate various aspects of chemical reactions. Figure 8.4 shows a typical text book diagram using the various types of representations for a simple chemical reaction.

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.

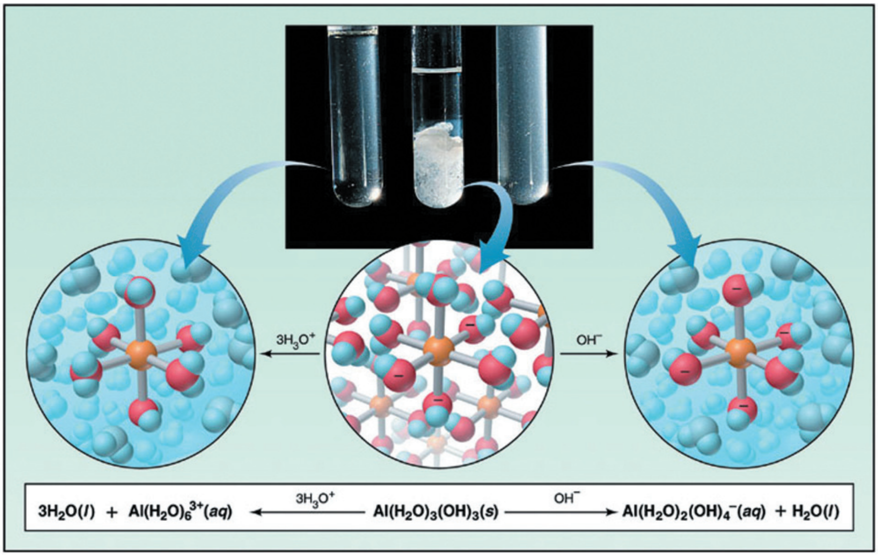


Fig. 8.5 A three level illustration (from M. S. Silberberg, Chemistry: The molecular nature of matter and change, 4th ed., McGraw Hill, 2006, p. xxv, reproduced with permission of The McGraw-Hill Companies)

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

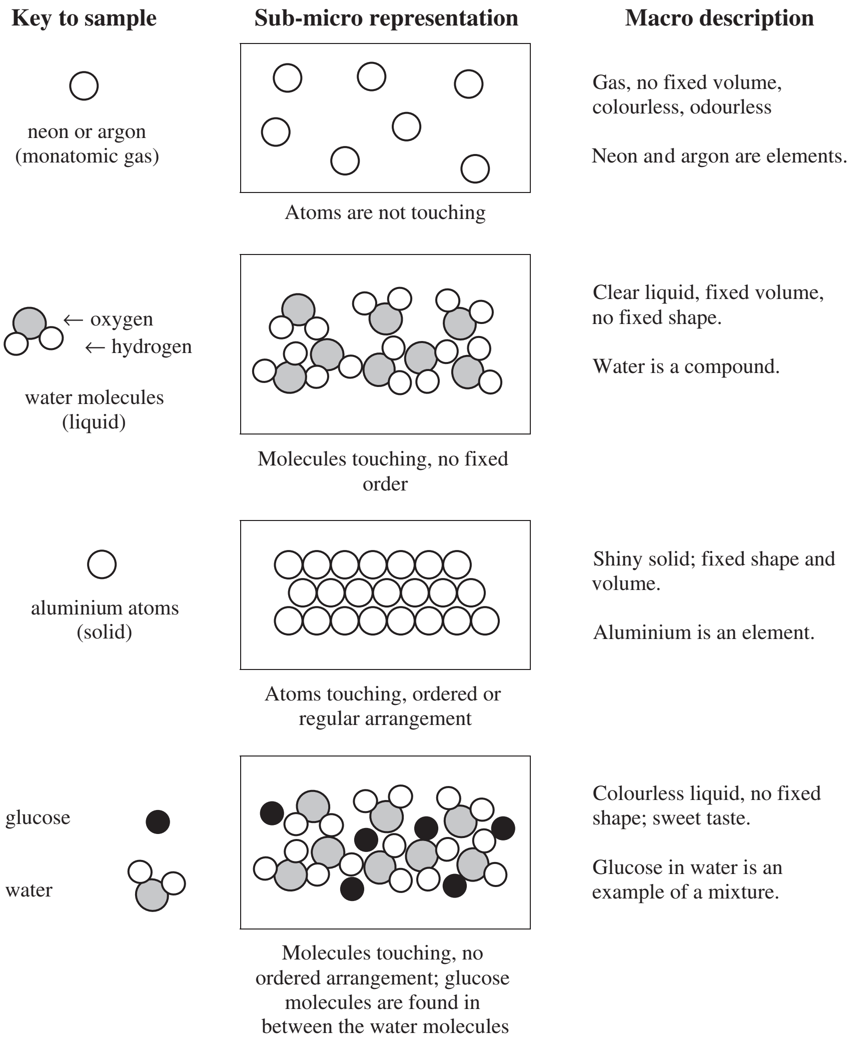


Fig. 8.6 An introduction to conventions commonly used in sub-micro representations

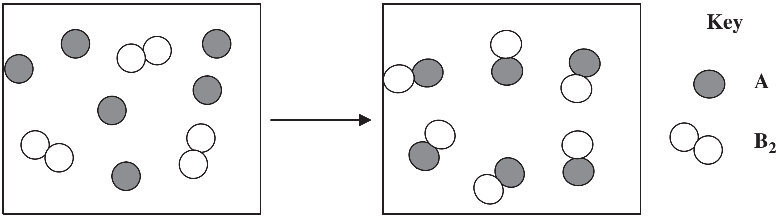


Fig. 8.7 Balancing an equation presented as sub-micro particles

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

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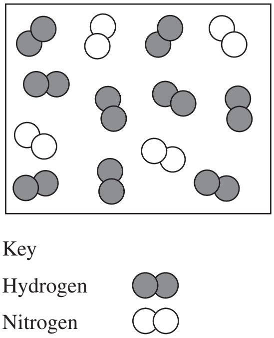
[1] UCT; abbreviation for University of Cape Town, South Africa



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-

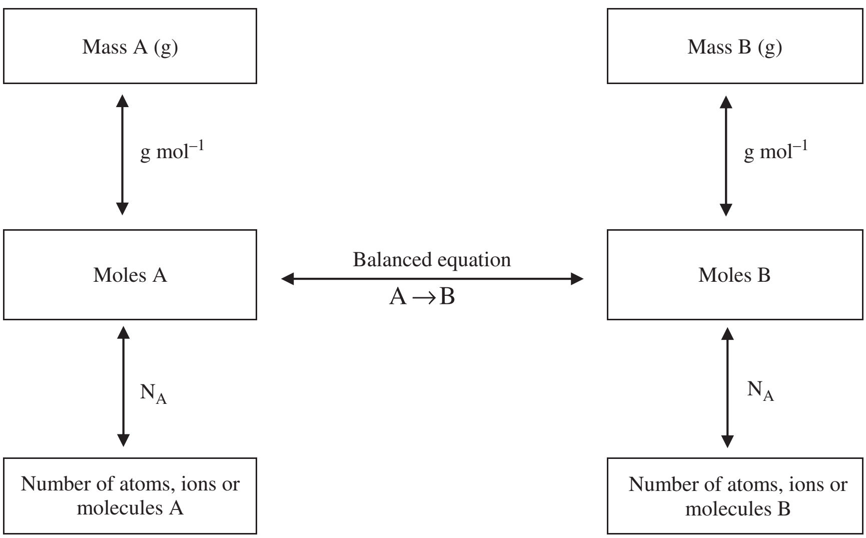


Fig. 8.10 A schematic diagram showing the relationship between mass, moles and the number of particles in a balanced equation

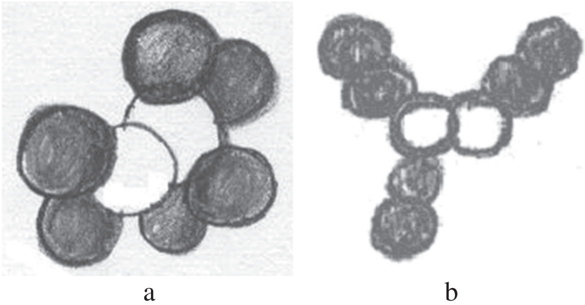


Fig. 8.11 Students' representations of the product of the reaction for question in Fig. 8.8

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.*

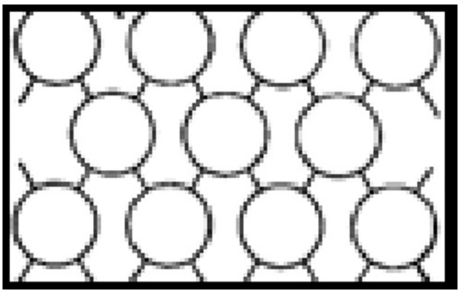


Fig. 8.12 Diagram used in the interview with students

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.

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