

Chapter 2

The Development of Theoretical Frameworks for Understanding the Learning of Chemistry

Gail Chittleborough

Introduction

There seems to be a mystique about chemistry. Many students do not recognise the chemistry in their everyday lives, many students consider chemistry to be a challenging and difficult subject beyond their capabilities and many students fail to recognise the value of chemistry in their future careers—even for those students who are majoring in a science and especially those who are not majoring in a science.

Chemical literacy can be defined as those skills and knowledge required for understanding chemistry in a social, democratic, cultural and utilitarian sense (Nuffield Curriculum Projects Centre 2001). But falling chemistry enrolments rates at both school and university level (DEST 2003) will result in fewer people having that basic chemical literacy and chemistry knowledge, and yet chemistry knowledge is expanding to include new processes, attitudes and approaches. This expansion of chemical knowledge is seen in the inclusion of emerging sciences in curricula such as green chemistry, with processes that are environmentally aware and designed to reduce waste production, and nanotechnology, biotechnology and neuroscience.

The lack of connectedness of chemistry with the real world and the lives of the learners is a common criticism (Gabel 1998) founded and reinforced in the traditional chemical content and teaching approaches that are resilient to change. This applies to both “what” is taught—both the conceptual knowledge and the procedural knowledge including operative and cognitive skills, and the pedagogical approach to how it is taught—from memorisation of definitions and solving algorithmic type problems to more student centred, active approaches that use open-ended challenges requiring application and problem solving. Commonly, the teacher practice is secure in the chemistry textbook—interpreting the curriculum

G. Chittleborough (✉)
Deakin University, Melbourne, VIC, Australia
e-mail: gail.chittleborough@deakin.edu.au

for the teacher, providing what is to be learnt, problems, practical activities, simulations, and experiments thereby directing or attending to the curriculum, and the assessment. With a textbook approach, there is the risk that the existing understandings of the students may not be considered and individual needs of the students may not be met and the depth of understanding may not be optimised.

This chapter explores chemical epistemology as a way of interpreting students' understandings of how chemical ideas and concepts develop. Chemical epistemology is an understanding of the knowledge of how chemical ideas and knowledge are built up and an understanding of the way of knowing about chemical processes. This understanding will inform teachers' pedagogical practice as explained by Erduran and Duschl (2004, p. 126): "For chemistry teaching to be effective, prospective teachers will need to be educated about how knowledge is structured in the discipline that they are teaching". The interplay between Subject Matter Knowledge (SMK), the philosophy of chemistry and Pedagogical Content Knowledge (PCK) is examined to help identify opportunities for the chemistry teacher to be better informed about the ways students learn chemistry. This should inform their teaching and their use of the textbook and resources. Data from a research study into first-year university students' understandings and learning approaches of chemistry is used to support the development of the chemical epistemology.

Representation Versus Levels of Representation of Matter

The study of chemistry is essentially about the abstract concept of the atomic theory of matter that can be portrayed at various levels of representation corresponding to the scale and symbol being considered. It is important to distinguish the three levels of representation of matter as described by Johnstone (1982, 1993) from the term "representation" which according to *The Australian Concise Oxford Dictionary* (Hughes 1995) has numerous meanings including: to symbolise; to call up in the mind by description or portrayal or imagination; to place a likeness of before the mind or senses; to serve or be meant as a likeness of; to describe or to depict as. These terms reinforce the metaphorical nature of a representation—providing a description of real phenomena in terms of something else with which the learner is more familiar. Under this broad definition, all representations such as models, analogies, equations, graphs, diagrams, pictures and simulations used in chemistry, can be regarded as metaphors because they are helping to describe an idea—they are not literal interpretations, nor are they the real thing. The metaphorical status and role of the symbolic representations used in chemistry is most important and needs to be understood if the metaphor is to be used successfully (Bhushan and Rosenfeld 1995; Treagust and Chittleborough 2001). Because scientific concepts are foreign to students and difficult for them to understand, metaphors are commonly used to provide links to familiar concepts and provide a foundation on which students can build new ideas. These considerations are in line

with a constructivist approach to teaching in which the students' prior knowledge is the foundation on which to build further knowledge (Yager 1991). Johnstone (1993) refers to the *level* of chemical representation of matter, which must not be confused with the term representation commonly used for symbolic representations of chemical phenomena including almost any explanatory tool. Johnstone's hierarchical level is a framework that provides an overview of how chemical data are portrayed and presented whereas the term representation can be used for any chemical depiction that the learner encounters.

Johnstone distinguished three levels of chemical representation of matter which are described as: (1) the macroscopic level—comprising tangible and visible chemicals, which may or may not be part of students' everyday experiences; (2) the sub-microscopic level—comprising the particulate level, which can be used to describe the movement of electrons, molecules, particles or atom; (3) the symbolic level—comprising a large variety of pictorial representations, algebraic and computational forms.

Johnstone (1982) describes the macroscopic as descriptive and functional, and the sub-microscopic level as representational and explanatory. An overview of the three levels of chemical representations of matter, presented diagrammatically in Fig. 2.1 encourages the use of multiple representations, using all three levels simultaneously (Hinton and Nakhleh 1999) and develops an understanding of the importance of the scale that is being represented. Examples of each of the three levels of chemical representation of matter are shown in Fig. 2.2. Harrison and Treagust (2002) point out that for many Grade eight students and even for some Grade 8–10 science teachers, their understanding of the particulate nature of

Fig. 2.1 Three levels of chemical representation of matter (Johnstone 1982)

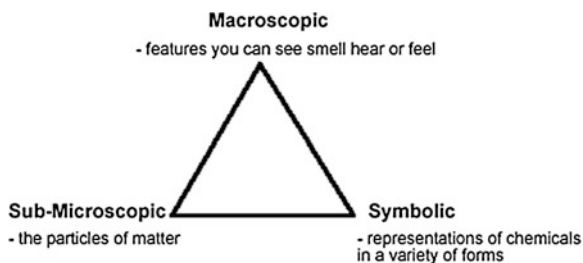
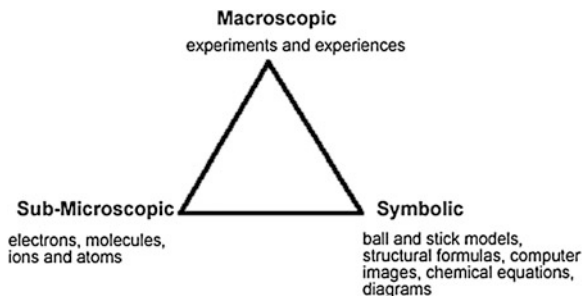


Fig. 2.2 Examples of each of the three levels of chemical representation of matter

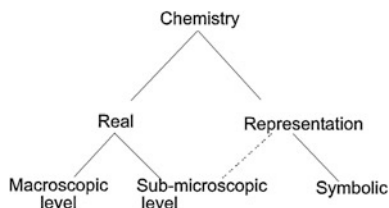


matter, i.e. the sub-microscopic level is poor. The use of the term sub-microscopic refers to levels from the microscopic through to the nanoscopic level and even smaller. Research shows that many secondary school and college students, and even some teachers, have difficulty transferring from one level to another. These findings suggest there is a need to emphasise the difficulty of transferring between different types of representations within each level, as well as transferring from one level to another (Treagust and Chittleborough 2001). At each level many different representations are used in a variety of modes to convey meaning. Johnstone (1997, p. 263) proposes the gradual development of the three interconnected levels and warns against introducing all three levels simultaneously with novices because the “working space” of our brains cannot handle all three levels simultaneously.

Reality Versus Representation

Inherent in Johnstone’s classification scheme is the understanding that the macroscopic and sub-microscopic levels of representation of matter are in fact reality not a representation. The reality of the level of representation is represented in Fig. 2.3 showing the relationship between the three levels of chemical representations and real and represented chemical data. The differences between reality and representations are not often confronted as it is usually assumed that they are understood. However, from discussions with colleagues, it would appear that there is some ambiguity between chemists and educators as to the reality of the sub-microscopic level, with some chemists confident that it is real and some educators believing that it is a representation of a theoretical model—hence the dotted line in Fig. 2.3. The difference between reality and theory needs to be considered here because the sub-microscopic level is based on the atomic theory of matter. The sub-microscopic level is as real as the macroscopic level—it is the scale that distinguishes it, and the fact that the sub-microscopic level cannot be seen easily makes it hard to accept as real. Chemists are now able to observe atoms or molecules, using an electron microscope (but not always in real time), and so they can be classified as real rather than a theory; however, it is not possible to see how the atoms interact, so for this the chemist relies on theories. Theories rely on models—so when we picture an atom we are in fact picturing a model of an atom or a number of pictures of atoms based on various models (Taber 2003).

Fig. 2.3 The relationship between the three levels of chemical representations and real and represented chemical data



The three levels of chemical representation of matter are described as follows: (1) the macroscopic level is real and able to be seen; (2) the sub-microscopic level is based on real observations but still needs the theory to explain what is occurring at the molecular level and uses representations of theoretical models; (3) the symbolic level is a representation of the reality.

Johnstone (2000) emphasises the importance of beginning with the macroscopic and symbolic levels because “both corners of the triangle are visualisable and can be made concrete with models” (p. 12). The sub-microscopic level, by far the most difficult (Nelson 2002), is described by the atomic theory of matter, including particles such as electrons, atoms and molecules and 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 beginning students try to learn and understand it. The lack of a mental model of many novice students appears to be a result of the sub-microscopic level being ignored or marginalised when compared to the macroscopic and symbolic levels of representation.

The sub-microscopic 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 (2000) 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. 58). Similarly, the discovery of sub-atomic particles such as the *god* particle, known as the *Higgs boson*, is evidence of the tentative nature of scientific knowledge, and a reminder that it is a construct of changing interpretation. This aspect of scientific knowledge is dynamic and exciting. Appreciating this overview of how scientific ideas are developing may help students to expand their epistemology of science.

The images of the sub-microscopic level available through advances in technology has the potential to provide the visualisation required to teach this level more adequately, even though the projections are still representations (Stevens et al. 2002). Nanotechnology describes research where the dimensions are less than about 1,000 nm (remembering that 1 nm is one-millionth of a millimetre) with descriptions and vision of particular atom.

A teacher’s professional expertise demonstrated through their pedagogical content knowledge (PCK) is in scaffolding the learning for students, by selecting the most appropriate form of representation(s) for the concept and for the learner, depending on their experience and background knowledge (Bodner 1986). By acknowledging the level(s) of the representation of matter as proposed by Johnstone, highlighting the weakness and strength of the representation and linking the representation to other forms and other levels—the learner has knowledge of the content, but also distinguishes the content from the features of the explanatory tools being used. The use of multiple representations becomes important in allowing students to distinguish these features (Chittleborough and Treagust 2009).

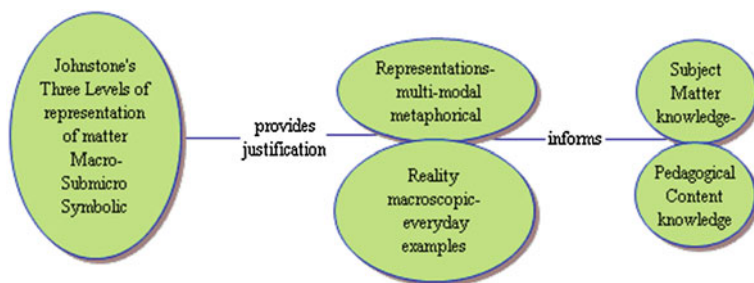


Fig. 2.4 Chemical epistemology ways of thinking about chemical knowledge to inform teaching

This approach empowers the student to appreciate the variety of explanatory tools that are commonly used to help understand abstract concepts.

PCK forges links between the content and how it is best taught. Erduran and Scerri (2002, p. 8) emphasise a philosophical approach to chemistry education and recommend that the “teaching and learning of chemistry can be improved through an understanding of the structure of chemical knowledge”. Figure 2.4 represents the links between the structure of chemical knowledge and the tools for teaching. This approach is not inconsistent to Johnstone’s ideas that provide students with a means of understanding the nature of chemical knowledge. The emphasis on the philosophy underpinning the knowledge of chemistry has the potential to re-energise the importance of the role of models and representations in the process of science (Treagust et al. 2002). While Johnstone has focused on the representation of the subject matter of chemical knowledge, the pedagogical content knowledge as proposed by Shulman, that connects across contexts, and looks at ways to best help students learn. Carolan et al. (2008) draw on the Peirce’s triadic model when discussing representational competence and the way meaning is constructed by learners using representations. This model has the physical object (referent), the meaning (concept) and the symbolic representations—such as verbal, visual, symbol. There is a similarity to Johnstone’s three levels of chemical representation of matter with both frameworks designed to add meaning to understanding. When teaching with an emphasis on the role of representations, students began to use the term “representation” in their vocabulary, describing the explanatory tools they are using and demonstrating an appreciation of their role in portraying the abstract (Prain and Tytler 2013).

Explanatory Power of Symbolic and Sub-microscopic Levels of Chemical Representation of Matter

It is the theoretical nature of the sub-microscopic level that is essential for chemical explanations. Symbolic representations of atoms and molecules are usually a snapshot of an instant in time focusing on the single successful reaction

only, for example, a reaction mechanism or an equation. By focusing only on the successful reaction, the unsuccessful reactions are forgotten and the probability of success is not represented. 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 are 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. Explanations of chemical phenomena usually rely on the behaviour of the sub-microscopic particles that are represented symbolically. Consequently, the students' understanding of all three levels is central to the success of any explanation.

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 or model is developed to represent the sub-microscopic particles in the substances being observed. Observations at the macroscopic level of changes in colour or volume of a reactant, or the evolution of a gas, for example reveal nothing about the sub-microscopic behaviour of the chemicals involved. Yet, explanations are nearly always at the sub-microscopic level—a level that cannot be observed—but is described and explained using symbols by which personal mental models are constructed.

Unfortunately, students often transfer the macroscopic properties of a substance to its sub-microscopic 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 et al. 1995). Colour at the macroscopic level is not a characteristic at the sub-microscopic level. To overcome this problem, Gabel et al. (1992) recommend that teachers provide physical examples or at least descriptions of the chemicals in the problems, in addition to the representations, so that students can establish their own links between the three major levels for portraying the chemical phenomena. In a study into students' understanding of acids and bases, Nakhleh and Krajcik (1994) reported that students' explanations made many more references to the macroscopic level than the sub-microscopic level and more about the sub-microscopic than the symbolic, indicating that they are more confident describing these chemicals at the macroscopic level. Given this not unexpected finding, which is supported by other studies, it is somewhat surprising that so few chemistry curricula emphasise the chemistry of students' everyday experiences (Garnett et al. 1995) or embed the chemical concepts in a familiar or relevant context for the learner. These results lend support to the proposal of placing greater emphasis on the macroscopic level of representation of matter.

Fortunately, there are now exceptions to the atomic structure approach of the 1960s and 1970s that emphasised the abstract symbolic and sub-microscopic levels (Fensham 1994). The use of familiar items in chemistry laboratory work has been used to reinforce the link between chemistry and home, resulting in improved students' perceptions of chemistry (Ramsden 1994; Roberts et al. 1996). In

England, the Salters Chemistry course incorporated a constructivist approach using familiar chemicals as the starting point to motivate students and create a positive classroom climate (Campbell et al. 1994). Nelson (2002) has had positive results with “teaching chemistry progressively” (p. 215) by beginning with student observations at the macroscopic level to provide the examples and foundation to learn the atomic and molecular level, followed by the electronic and nuclear level. Wright (2003) supports the approach of introducing students to atoms and molecules early in their middle years of schooling so that students have a sound foundation before introducing the sub-atomic level. Forgoing content chemistry for contextual chemistry alone is not the solution; moreover, a change in the philosophical approach is needed whereby the unique nature of the structure of chemical knowledge underpins the direction of changes to the curriculum (De Vos et al. 2002; Erduran and Scerri 2002).

Data Source

The progress of first-year university students undertaking an introductory chemistry course was monitored over two consecutive years. The aim of the study was to investigate how first-year university students, who have little or no chemistry knowledge, perceive the role and use of models in science, interpret diagrams of chemical phenomena at the macroscopic and sub-microscopic level, make links between the three levels of chemical representation, develop mental models of chemical phenomena and choose learning strategies. Quantitative and qualitative data were collected from 18 students in year 1 and 19 in year 2 through interviews throughout the academic year, instruments on their use of model and modelling ability, and their work samples were analysed. The data is used here and is also reported elsewhere (Chittleborough and Treagust 2008; Chittleborough and Treagust 2009; Chittleborough et al. 2002, 2005).

The Implications of Johnson’s Triangle for Teaching

Because representations are the focus of many chemical explanations, students’ understanding of them is critical to their value. Equally important is the students’ appreciation of the role of the model and/or representation in the scientific process and their understanding of the concepts of theory, model, fact and reality that are inherent in their epistemological understanding. The research data, from the study with first-year university students undertaking an introductory chemistry course are drawn on here to show that generally most students had a good understanding of the macroscopic and symbolic levels of chemical representation of matter, however, students’ understanding of the sub-microscopic level varied, with some

students being able to spontaneously envisage the sub-microscopic view while for others their understanding of the sub-microscopic level of chemical representation was lacking. Students with little or no chemical background could not talk seriously about the sub-microscopic level because it was not real to them. Leanne and Kathy, are two such students from the university study whose responds to the following questions:

Int.: Last time I interviewed you, we talked about the mental picture you have of a chemical phenomenon. Can you give me an example of a chemical phenomenon?

Kathy: No not really. If you think of the reaction of photosynthesis—I know the equation; I know what really happens and the equation describes what happens. But I don't picture the little carbon dioxide molecules combining with the water molecules, it just happens; we just know that it does (3.9.1.50).

With experience, the sub-microscopic level becomes real to the learners because they begin to understand its value in explaining why and how the atomic and molecular movements occur. However, Kathy had no need to know any more about the sub-microscopic level than she already knew. Both Kathy and Leanne considered the questions about the sub-microscopic level to be trivial. Similarly, Leanne who left high school the previous year and had not studied chemistry before had no comprehension of the levels of representation. She had studied science to Year 10 level where she was in the non-chemistry group. In the first interview, Leanne applies macroscopic properties to the sub-microscopic nature of matter, displaying a poor modelling ability. There is obvious confusion between the representational nature and the reality of the sub-microscopic level. She was unable to understand the representational nature of the diagrams of various atoms, and molecules, as is shown in the following excerpts.

Int.: If I gave you a sample of copper for example. Can you explain how the copper atoms are arranged?

Leanne: They would be all together.

Int.: What would they be like?

Leanne: No idea.

Int.: Coppers hard we know that but what about the atoms?

Leanne: Coppers hard, then doesn't mean that they are tightly packed. They would be together. (3.8.12.13–19).

Int.: What would sodium chloride atoms look like?

Leanne: It would look like little white things.

Int.: If you get down from the little white things and go down to the atoms what are the atoms going to look like?

Leanne: White.

Int.: OK (3.8.12.24–26).

Leanne's comment demonstrates a common assumption by learners in associating the macroscopic qualities to the sub-microscopic level (Andersson 1990). This misconception arises because the student doesn't understand the differences of the three levels of representation of matter. Learning chemistry requires modelling ability and representational competence—to be able to use the multi-model representational forms that are explanatory tools (Gilbert 2007). Johnstone's (1993) triangle which tries to explain why students find learning chemistry so difficult has become a significant theoretical framework in understanding how chemistry concepts are represented. In considering how and why Johnson's triangle is used, I have proposed two interpretations: the expanding triangle and the rising iceberg.

The Expanding Triangle

Commonly, students are exposed to all three levels of chemical representation of matter simultaneously as part of their chemistry curriculum. A common scenario would be in junior high school for students to perform experiments to observe simple chemical and physical changes; to be taught about the characteristics of the particulate nature of matter and to learn the symbols of atoms—briefly touching on all three levels of chemical representation of matter. Curricula are often arranged as a spiraling concern, consistent with a constructivist philosophy, beginning with basic ideas, returning and repeating what has already been learnt and building on it in a recursive and repetitive manner. In terms of Johnstone's triangle, the students learn some chemistry at all three levels of chemical representation of matter simultaneously and return and learn a bit more at all three levels of chemical representation of matter and so on moving from I to II to III (Fig. 2.5). So the students' depth of knowledge increases and the triangle (representing students' knowledge) grows as the student learning proceeds.

As students continue to understand more chemistry at each of the three levels they can make the connections between the three levels, but this is not guaranteed

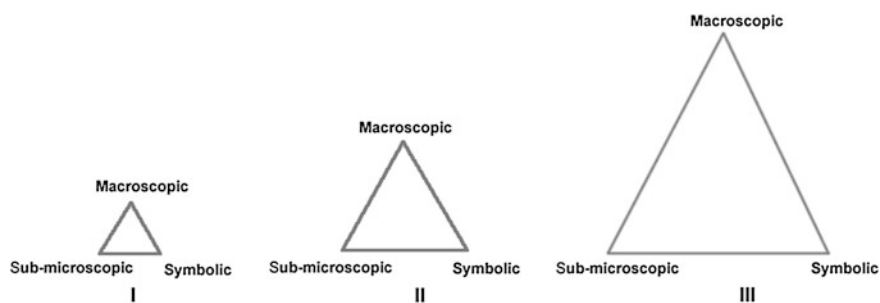


Fig. 2.5 The expanding triangle—a framework for learning chemistry

(Boo 1998; Gabel 1998). The theoretical framework is titled—*the expanding triangle*—because as the students learn more and more at each of the three levels, the triangle expands; however, there is no guarantee that they relate the three levels to each other.

The Rising Iceberg

The three-dimensional image of an iceberg that the title creates—emphasise not only the depth of chemical concepts, but more importantly the sequence of the use of the three levels of representation of matter, with the macroscopic being the central focus in introductory programs and the symbolic and sub-microscopic being introduced subsequently. The shaded triangle—determined by the position of the horizontal line in Fig. 2.6 represents students' growing understanding. It is consistent with Johnstone's (1991) recommendation of starting with the macroscopic and symbolic levels and emphasises using the level(s) of chemical representation of matter that best suits the students' ability level. The macroscopic level of chemical representation of matter at the top corner of the triangle is always included, whereas the sub-microscopic and symbolic levels are only introduced as needed. A horizontal line is drawn across the triangle to indicate the depth of chemistry understanding to be achieved. Obviously the position of this horizontal line depends on the students' abilities, age and stage of chemical knowledge development. The shaded area above the horizontal line is deliverable and achievable for the particular students being considered. As the literature recommends that the macroscopic level is most appropriate for beginning students, so the chemistry should maintain an observable and experimental focus without having to use the particulate nature of matter. When students move to higher levels of understanding then more of the symbolic and sub-microscopic levels can be introduced.

This rising iceberg framework is based on the constructivist philosophy and is consistent with the literature recommendations of starting with the macroscopic, visible and observable chemical occurrences that are often part of students'

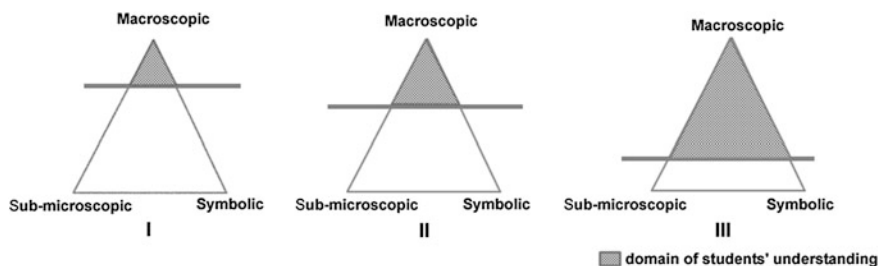


Fig. 2.6 The rising iceberg—a theoretical framework for learning chemistry

everyday experiences and observations, thus providing a contextual learning experience. This was shown to be successful with the Salter approach (Ramsden 1992). The intention of this framework is not to marginalise the sub-microscopic level—especially as it is nearly always the basis of chemical explanations, rather to reassess its role and importance, with evaluation of what detail of the sub-microscopic level is needed to be known in order to understand particular chemical concepts.

The rising iceberg framework is designed to emphasise the importance of the macroscopic level, provide a contextual setting for learning and to critically evaluate how the sub-microscopic level is explaining the chemical phenomena. However, the literature reports that traditionally there is conflict between chemical ideas and everyday ideas; for example, everyday words adopt new and specific meanings in chemical settings; everyday experiences support a continuous nature of matter whereas the more theoretical particulate nature of matter depends on models and representations to help generate mental models; and confusion is evident between the sub-microscopic and macroscopic nature of matter. In order to combat these potential misunderstandings, a constructivist approach is recommended, with the students' understanding as a starting point. The literature emphasises the importance of students' prior knowledge and understanding for their future understanding. The representations at the symbolic level probably contribute most to the students' mental model. Using the rising iceberg framework, initially inexperienced students' mental models are undeveloped corresponding to the small triangle; as they learn more chemistry, then their mental model expands as they focus on the sub-microscopic level.

Johnstone's Triangle Informing the Chemical Epistemology

The triangle can provide insights into chemical epistemology by helping students in their process of knowing about chemical knowledge. The explanatory function of the three levels supports a framework of knowledge that can help the development of a students' epistemology. Through modelling, students are able to gain an understanding of the analogous relationship between the model (analogue) and reality (target) (Gilbert and Boulter 1995). Grosslight et al. (1991) suggest that "different levels of understanding models reflect different epistemological viewpoints" (p. 799). This important link between modelling and epistemology is data from students expressing an understanding of the role of models in the process of science as reported in Chittleborough and Treagust (2007) and also from students using models to make predictions, test ideas and undertake scientific inquiry (Chittleborough and Treagust 2008).

For many students in the study at university year 1, there were dramatic improvements in their epistemology of chemistry; through hard work and application of knowledge, students developed a way of thinking about chemistry. This

could be described as an enculturation whereby the sub-microscopic level of matter promotes a chemical way of thinking—a chemical epistemology. For other students, however, the learning experience was driven by the course requirements encouraging a rote-learning regime that did little to improve their epistemology of chemistry. These students circumvented the sub-microscopic level of matter.

Notwithstanding the importance of the framework consisting of the three levels of chemical representation of matter that has been described in the previous section, it is vital to question the relevance of some theoretical and highly mathematical chemistry to all students. There is a need to assess the appropriate depth of chemistry that is required to learn. Johnstone (1982) uses an analogy of the use of a car—for most of the time the car exists at the descriptive and functional level (macroscopic)—detailed explanations of the mechanisms of the car (sub-microscopic level) are not needed or cared about by the general public. In chemistry, even without the sub-microscopic understanding, excellent scientific questions can be posed and experiments tested at the macroscopic level. Johnstone (1982, p. 379) suggests “it would be arrogance ... to assume that chemistry must have all three levels if it is to be respectable”. So using this concept, the non-major chemists could still be thinking chemically, in a scientific manner, but have a more practical approach. The analogy of the car is consistent with the rising iceberg framework. Johnstone (1982) is in favour of exploiting the macroscopic level and introducing the sub-microscopic as needed. Through using more macroscopic references the chemistry could be more contextual and help to promote a higher standard of chemical literacy along with giving chemistry a better image.

Pedagogical Implications

Will raising teachers’ awareness of how chemical ideas are learnt, impact on their pedagogical practice and translate into effective teaching strategies and deeper student understanding? It is futile if the impact of chemical educational research onto practice is not assured; but still there are many links in the chain to students achieving deeper understanding. The interactions between teachers and students, those learning moments, can be elusive to recognise, but it is these very experiences that inform teachers practice. Shulman describes the situation of the isolated classroom teacher working in “pedagogical solitude” (Shulman 2005, p. 29). The frameworks discussed earlier, SMK, PCK and Philosophy, alongside the three levels of representations and the role of representations provide a foundation understanding of how students learn Chemistry. Alongside are more general theories of learning such as constructivism and behaviourism. Learning is complex, different and unique for individuals, so no single formula or template will guarantee success. In teaching chemistry, teaching approaches focus on many aspects such as modelling ability, multiple representations, visualisation, the process of science (inquiry), contextual focus, etc.

Conclusion

Most significant to the learning of chemistry is the ontological framework that the three levels of chemical representation of matter provide for the learner and the teacher. By providing the learner with basic criteria on which to understand the explanatory tools commonly used in chemistry, then the understanding of the chemical content may be improved. Armed with this understanding, the learner can develop a way of thinking about chemical phenomena—described as the chemical epistemology—an understanding of the knowledge of how chemical ideas are built and an understanding of the way of knowing about chemical processes.

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