CHAPTER 2

REVIEW OF RELATED LITERATURE

2.0 Introduction

In this chapter, literature review related to the study shall be presented. Section 2.1 provides a review related to difficulties and dilemmas in learning chemistry. Section 2.2 examines representations in chemistry. Alternative conceptions related to basic chemical concepts and chemical representations are discussed in Section 2.3. Section 2.4 critically reviews literature related to representational competence in chemistry while Section 2.5 looks at possible cognitive variables influencing representational competence in chemistry. Section 2.6 provides a summary of the chapter.

2.1 Learning Difficulties in Chemistry

> Chemistry, by its very nature, is highly conceptual. While much can be acquired by rote learning, real understanding demands the bringing together of conceptual understanding in a meaningful way. Thus, while students show some evidence of learning and understanding in examination papers, researchers find evidence of misconceptions, rote learning, and of certain areas of basic chemistry which are still not understood even at degree level (Johnstone, 1984; Bodner, 1991): What is taught is not always what is learned. (Sirhan, 2007, p.3)

A subject of abstraction and symbolic complexity, chemistry is often regarded as a difficult subject. Chemistry educators and teachers, as well as students taking up chemistry probably agree that it requires a lot of effort and skills to teach and to learn chemistry. At the introductory level, chemistry is also commonly believed to be more difficult compared with other sciences (Chang, 2010). For beginning chemistry students, as compared to other sciences, this may be their first formal encounter with a science that is, in many ways, very much removed from their everyday experience. Unlike physics and biology, much of chemistry is untouchable and unobservable, relying on a system of representations to explain chemical phenomenon. Many research studies have revealed major learning difficulties and identified key causes of these difficulties (Gabel, 1993, 1998, 2000; Johnstone, 1982, 1991, 1997, 2000a, 2000b; Sirhan, 2007; Treagust, Duit & Nieswandt, 2000). Everywhere, more and more students are giving up chemistry (Johnstone, 2000a, 2000b). Some of the dilemmas of understanding chemistry shall be examined. These include: (i) the nature of chemistry - multi-level learning or multiple levels of representation, (ii) the challenge of multiple representations, (iii) the abstract nature of chemistry, (iv) alternative conceptions, and (v) the language of chemistry.

2.1.1 The nature of chemistry: Multi-level learning

One of the key reasons for learning difficulty in chemistry is the nature of chemistry itself. Johnstone (1982, 1991) pointed out that in chemistry, students learn in three different representations simultaneously, and how to inter-relate each new concept or fact in all three domains: macroscopic, submicroscopic, and symbolic. It is this aspect of multi-level learning in chemistry that represents a significant challenge to many chemistry learners, in particular beginning chemistry students. Secondary school students generally have limited understanding of multiple levels of representation in chemistry. As a result, they experienced conceptual difficulties transferring between these levels (Ben-Zvi, Eylon & Silberstein, 1988; Gabel, 1998; Nakhleh, 2002). Even beginning undergraduate students also have been found to experience difficulty understanding multiple levels of representation associated with chemical concepts (Bodner, 1991). To understand chemical concepts and chemical phenomena, students should be able to demonstrate facility in using these representations, and be able to move fluently between these representations, both at the same level as well as across levels. However, research has shown that many secondary school teachers tend to move between the macroscopic, submicroscopic, and symbolic levels without highlighting their inter-connectedness (Gabel, 1999). Learners are thus left with the demanding task of trying to relate the three levels, and navigating between the levels. Overload of students' working memory space has been identified as an area of concern related to learning difficulties in chemistry (Johnstone, 1991, 1997, 2000a, 2000b, 2006; Sirhan, 2007). Johnstone (2006) suggests a need to rethink the curricula to begin with a treatment of one corner only followed by the use of a side, before leading the students into the middle of the triangle (see Figure 2.1). Multiple levels of representation of matter shall be discussed further under the section on representations (Section 2.2).

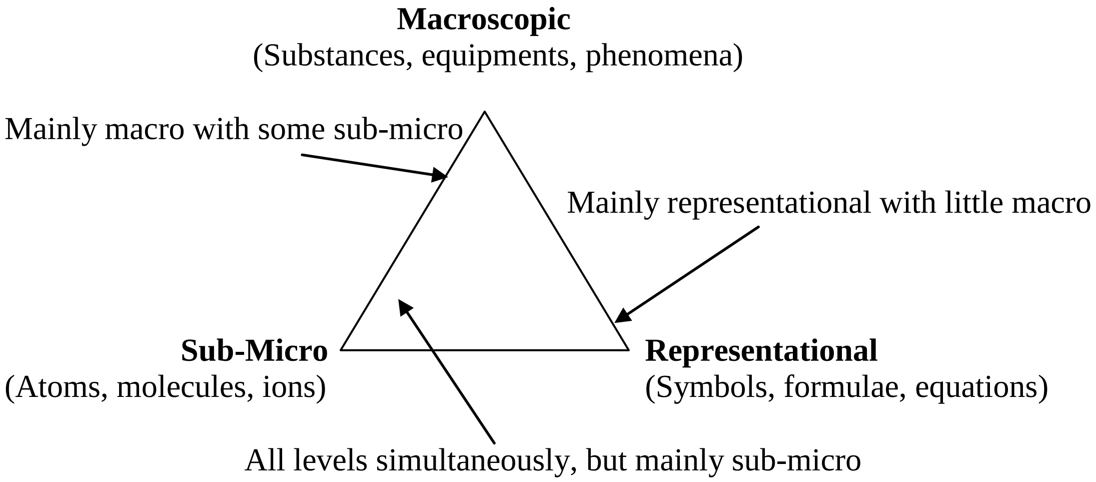


Figure 2.1: The three conceptual levels of chemistry
(Johnstone, 2006, p.59, Figure 6)

2.1.2 The challenge of multiple representations

The terms "multiple levels of representations" and "multiple representations" should be distinguished. While "multiple levels of representations" refers to the three levels of representations of matter (macroscopic, submicroscopic, and symbolic), “multiple representations” refers to the use of more than one way to represent an idea such as using text and diagram.

In a study of the topic of organic chemistry, Harrison and Treagust (1996) observed that students who are exposed to, and who become skilled in the use of multiple analogies, developed a more scientific understanding of the science concept under investigation than do students who concentrated on one single well established analogy. Gonzales, Prain, and Waldrip (2003) also suggested that student learning would be enhanced if teachers expanded the number of ways they ask students to represent knowledge of the same concept.

However, the connections between the macroscopic level and the diagrams of the submicroscopic level are not always apparent to students. To ensure learner understanding, chemical diagrams need to be used carefully and more explicitly (Chittleborough & Treagust, 2008; Davidowitz & Chittleborough, 2009)

In a study involving 17 non-major chemistry students taking an introductory university chemistry course, Chittleborough and Treagust (2008) found that some students had a poor level of understanding of chemical diagrams even after completing both exercises and experiments using the diagrams. They cautioned that limited background knowledge of the macroscopic, microscopic, and symbolic aspects of chemistry could influence students’ interpretations of chemical diagrams at the various levels. According to Chittleborough and Treagust (2008), a lack of ability to visualize or talk about the submicroscopic level influenced students’ ability to interpret diagrams at the submicroscopic level. For example, they found students with limited chemical background commonly interpret the chemical diagrams at a macroscopic or sensory level seeing only the laboratory equipment. According to Davidowitz and Chittleborough (2009), when representations (symbolic) are not understood, when links are not made between the macroscopic and submicroscopic levels, or when the diagram is unfamiliar, misinterpretation of diagrams can occur. Davidowitz and Chittleborough (2009) suggested having students draw and annotate chemical diagrams representing chemical phenomena at the submicroscopic level to provide some insight into their understanding of chemistry at the macroscopic level.

2.1.3 The abstract nature of chemistry

> "Chemistry, in like manner, is a mix of a molecular engineering, based on extrapolations from the macroscopic to the microscopic, and a science, coming to grasp directly with the microscopic." (Hoffmann & Laszlo, 1991, p.11)

Chemistry is recognized by chemists as the molecular science (Habraken, 1996) or microscopic science (Wu, 2003; Wu & Shah, 2004). Although the macroscopic observable phenomena form the basis of chemistry, explanations of these macroscopic phenomena rely on the symbolic and submicroscopic levels of representations which deal with invisible particles such as electrons, atoms, molecules, and ions (Treagust, Chittleborough & Mamiala, 2003). Unlike chemists who are regarded as highly visual people (Zare, 2002), beginning chemistry students who cannot think abstractly are unable to visualize these physical entities in the imaginary submicroscopic world.

Many of the concepts studied in chemistry are very abstract. According to Herron (1975), formal reasoning is a prerequisite for understanding chemical concepts. Piaget's model of cognitive development indicates that by late adolescent (11-14 years), young adults should have reached the final stage of maturation (Vass, Schiller & Nappi, 2000). However, research findings showed that less than one-third of our upper secondary level students were still at the late concrete operational level (Chan, 1988) although according to Piaget's theory of cognitive development they should have attained formal operational level based on their age. More recent studies by Eng (2002) and Nagalingam (2004) revealed even more disappointing findings. Nagalingam (2004) used the Classroom Test of Scientific Reasoning (CTSR) to assess the developmental level of a sample of Form four science students (n=391). Only 6.8% of the subjects were found to be formal thinkers.

2.1.4 Alternative conceptions

Many researchers agree that the most important significant things that students bring to class are their conceptions (Ausubel, 1968, 2000; Driver & Oldham, 1986). Duit and Treagust (1995) define conceptions as “the individual’s idiosyncratic mental representations”, while concepts are “something firmly defined or widely accepted” (p.47). According to Duit and Treagust (1995), children develop ideas and beliefs about the natural world through their everyday life experiences. These include sensory experiences, language experiences, cultural background, mass media, as well as formal instruction. Furthermore, Osborne, Bell and Gilbert (1983) argued studies have revealed that students bring with them to science lessons certain ideas, notions and explanations of natural phenomena that are inconsistent with the ideas accepted by the scientific community. Driver and Easley (1978) believed these existing ideas are often strongly held, resistant to formal instruction and form coherent though mistaken conceptual structures in the LTM. It is possible that students may undergo instruction in a particular science topic, do well in a test on the topic, and yet, do not change their original ideas pertaining to the topic even if the ideas are in conflict with the scientific concepts they were taught (Fetherstonhaugh & Treagust, 1992; cited in Tan, Taber, Goh & Chia, 2005). Duit and Treagust (1995) attribute this to students being satisfied with their own conceptions and hence, seeing little value in the new concepts. They also propose that students may just look at the new learning material “through the lenses of their pre-instructional conceptions” (p.47) and may find it incomprehensible. Osbourne et al. (1983) state that students often misinterpret, modify or reject scientific viewpoints on the basis of the way they really think about how and why things behave. Hence, it is not surprising that research shows that students may persist almost totally with their existing views.

In this study, the term `alternative conceptions’ is used to describe student conceptions that differ from scientific concepts (see Chapter 1 - Section 1.7: Definition of Terms).

Teachers need to be aware that they can be the sources of alternative conceptions, for example, by the way they teach. According to Wandersee, Mintzes and Novak (1994), teachers can also have the same alternative conceptions as students and can unwittingly pass their own alternative conceptions to their students, or think that there is nothing wrong with their students’ conceptions.

Although it is understandable how alternative conceptions have arisen, they are not scientifically accepted and have to be unlearnt or challenged so that new conceptions can be better understood. Teachers should be aware of common alternative conceptions and have strategies in place to help students reconstruct their conceptual frameworks (Taber, 1998). Teachers’ awareness of students’ backgrounds, ideas and experiences helps create a supportive classroom climate. Learning chemistry is not simple, and well-informed teaching practices such as reinforcing the links between the three major levels portraying chemical phenomena – macroscopic, submicroscopic, and symbolic- are needed to ensure students do not develop entrenched alternative conceptions. The world of alternative conceptions is a window into how our students actually think, and studying these alternative conceptions is valuable training in listening to students dialogues powerfully. Therefore, exploring and identifying students’ alternative conceptions and providing implications for the teaching and learning of the concepts examined is an important task of those involved in chemical education. Studies in which students’ alternative conceptions are described cover a wide range of subject areas including chemistry. Alternative conceptions in chemistry will be further discussed in Section 2.3.

2.1.5 Language

Chemistry has its own special language. Apart from chemical symbols, chemical formulae, and chemical equations which are the alphabets, words, and sentences in the chemistry language, common terms can also have special meaning in the chemical context. Indeed, the field of chemistry has a particularly demanding vocabulary. Learning difficulties frequently arise when some words used in everyday life also have different meanings in chemistry. However, in classroom, often no distinction is made between the scientific meaning and the commonplace meaning of vocabulary, assuming that students understand the special chemical meanings of the terms being used (Nakhleh & Krajcik, 1994; Schmidt, 1997). A more recent study by Chittleborough and Treagust (2008) also found a lack of ability among students to use chemical terminology accurately. Students tend to use everyday language and chemical phrases carelessly as many of these students were unfamiliar with, and unable to use the chemical vocabulary correctly and precisely.

Within chemistry, there are also several meanings for the same word and students confronted with the same words with different meanings become confused (Selinger, 1998; cited in Treagust, Duit, & Nieswandt, 2000). For example: `pure’ can refer to the cleanliness of a substance, not its chemical nature; `mixture’ refers to something physically combined together, not the chemical nature of, for example, glass, blood, or drinking water. Students' experiences are mainly with mixtures; however, their perception is that these substances such as brass, wine, and tap water are chemically pure. Words as different as dissolving and melting, which are obvious to teachers, are frequently confused when used by students who have insufficient background knowledge in chemistry, or experience, with which to distinguish these terms. Consequently, the teachers' meaning is not communicated clearly (Fensham, 1994). Particular words such as particle, molecule, ion, atom, and substance are often misused and misinterpreted. For example, when teachers speak about water being made of oxygen and hydrogen, students can interpret this to mean that water is a mixture of these two gases. Research has shown that precise and consistent use of language along with detailed particular descriptions of the submicroscopic nature of matter can improve students' interpretations (Fensham, 1994).

2.2 Representations and Chemistry

Due to its abstract nature, chemistry relies on a system of representations. Nowadays, chemical representations such as formulae, symbols, equations, and structures are widely seen not only in professional journals but also in chemistry text books used by school children, and routinely used to describe and explain chemical reactions and phenomena. Being familiar with chemical representations and their usage in chemistry is essential for constructing and communicating understanding.

2.2.1 What is a representation?

There are still some misunderstandings and much confusion on the use of the term “representation”. To better understand the role that representations play in chemistry learning, it is necessary to define the term “representation”.

2.2.1.1 Definition or meaning of the term “representation”

According to the Australian Concise Oxford dictionary (Hughes, Mitchell & Ramson, 1995; cited in Chittleborough, 2004), the word “representation” means something that represents another. The word “represents” has numerous meanings including: to symbolize, to call up in the mind by description, portrayal, or imagination. The Advanced Learner’s Dictionary of Current English (Hornby, Gatenby & Wakefield, 1963) defines “represents” as gives or makes a picture, sign, symbol, or an example of something. These terms suggest the descriptive and symbolic role of representations in explanations.

Estes (1989), cited in Bodner and Domin (1996) reminds us that “a representation stands for but does not fully depict an item or event.” While a photograph presumes all of the information in the scene, up to the resolving power of the film, representations are merely attempts the brain makes to encode experiences.

2.2.1.2 Internal and external representations

It is also crucial to distinguish between internal and external representations.

Simon (1978) uses the term “representation” in the sense of an internal representation – information that has been encoded, modified and stored in the brain. Martin (1982) uses the term “representation” in the same sense when he says that representations “signify our imperfect conceptions of the world”.

Bodner and Domin (1996) pointed out that the modifier “internal” is added to the term “representation” to distinguish the information stored in the brain (internal representation) from external representation, which are physical manifestations of this information.

An external representation may consist of a sequence of words (verbal) the individual uses to describe the information residing in his or her mind, or a drawing, or a list of information that captures particular elements of the mental representation. Individuals with different internal representations may produce similar external representations or vice versa. According to Gordin and Pea (1995), cited in Winn (2002), “inscriptions” or scripts are external representations such as drawings and diagrams that we place into our environment in order to help us think through problems.

Scaife and Rogers (1996) suggest that one advantage of making internal representations external as inscriptions is to enable us to re-represent our ideas. When our concepts are represented externally, we can interpret them and clarify our thinking like any other objects found in our environment.

Roth and McGinn (1998) remind us that inscriptions or external representation let us share our ideas with other people in our environment, making cognition a social activity.

It should be noted that the meaning of a representation is not embedded in the representation itself but is assigned to the representation through its use in practice. Individuals who become integrated into a community of practice progressively use its representational system in meaning-making activities. Subsequently, representations become useful tools for constructing and communicating understanding.

2.2.2 Representations in chemistry

"In an important sense, chemistry is the skilful study of symbolic transformations applied to graphic objects." (Hoffman & Laszlo, 1991, p.11).

According to Kozma and Russell (2005), there are two types of representations that chemists use to understand chemical phenomena – those that are internal, mental representations and those that are external, symbolic expressions.

It is believed that chemists have developed the ability to visualize or to "see" chemistry in their minds in terms of images of molecules and their transformations. Kozma and Russell (2005) refer to such internal representations as concepts, principles, or "mental models" that encompass the state of chemical understanding of the individual. Chemists also construct, transform, and use a range of external representations or symbolic expressions such as drawings, equations and graphs as tools for communication within the scientific community. They spontaneously write equations and draw structural diagrams to visually depict components of their mental models and the composition and structure of the compounds they synthesized. While they were others (Roth & McGinn, 1998) who refer to such symbolic expressions as "inscriptions", Kozma, Chin, Russell and Marx (2000) and Kozma and Russell (2005) refer to them as "visualizations" or merely representations.

Therefore, visualizations are perceptible, symbolic images and objects in the physical world that are used to represent aspects of chemical phenomena, much of which are invisible.

Eminent chemist and former President of the National Science Board, Richard Zare (2002, p.1290) characterizes chemists as "…highly visual people who want to "see" chemistry and to picture molecules and how chemical transformations happen. Kozma and Russell (2005) explained that the representations that Zare "sees" in his mind are mental models or internal representations while the figures he draws on paper or construct on a computer screen are visualizations or external representations.

According to Kozma and Russell (1997), representations included videos of the experiments, animations of the molecular events, dynamic graphs of a physical property of the system, and chemical equations or formulae. Russell and Kozma (2005) refer to graphs, equations, and animations of molecular phenomena as "chemical visualizations" and used the terms "chemical visualizations" and "representations" interchangeably in their article.

Representations in chemistry are examples of external representations or "physical manifestations of information" while internal representation is "information that has been encoded, modified and stored in the brain" (Bodner & Domin, 2000, p.24).

2.2.2.1 History of chemical representations

Prior to the work of 18th century chemist Antoine Lavoisier and his contemporaries, chemicals were named based on their physical properties. By the late 18th century, Lavoisier and colleagues developed a nomenclature system based upon elemental composition rather than physical properties (Hoffman & Laszlo, 1991).

The evolution of the chemical formula allowed chemists to display how molecules decomposed and combined and these symbolic expressions corresponded to the experimental procedures used in the laboratory to decompose and combine physical substances. Thus the language and symbol system were structured such that operating on symbols would be analogous to operating on substances.

By embedding in chemical nomenclature and symbol system, a shift in forms from physical surface features to aperceptual elemental composition, Lavoisier created a new way of thinking about chemistry, a new set of practices, and a new chemical community (Hoffman & Laszlo, 1991). Hence, developments in chemistry have continued to be shaped by developments in the way chemical phenomena are represented or visualized. For example, structural formulae show both the composition and the bonding pattern of atoms in molecules.

Between the 1930s and mid-1960s, chemists developed physical 3-D structural models composed of elemental components (sometimes balls and sometimes sticks) representing bonds between elements (Francoeur, 1997, 2002; cited in Kozma & Russell, 2005). These structures made the dimensional arrangement of elements more explicit and allowed for rotation and inspection of the molecule. In the 1960s, with the advent of sophisticated computer and molecular modeling software, interactive molecular graphics have come to replace physical models.

Chemical representations refer to various types of formulae, structures and symbols used to represent chemical processes and conceptual entities such as atoms and molecules. Chemical representations can be viewed as metaphors, models, and theoretical constructs of chemists' interpretation of nature and reality (Hoffmann & Laszlo, 1991). They allow chemists to have a common language for their joint inquiry (Nye, 1993) and serve as tools to conduct scientific investigations and communicate with professional community members (Kozma, Chin, Russell, & Marx, 2000).

2.2.2.2 Representations as a language

Chemical representations are like the language of chemistry; chemists use them to communicate with each other. For example, a chemical formula is like a word. It purports to identify, to single out the chemical species it stands for. However, the language of chemistry has a very specialized vocabulary. As a symbolic language, atoms of elements are represented by chemical symbols such as C, H, O, N, Na and Cl. These symbols are the alphabets of chemistry. To represent compounds, chemical symbols are combined into chemical formulae, such as CH_4, H_2O, NH_3 and NaCl. Formulae are the words of chemistry. When we extend the symbolic language to include sentences, chemical equations are formed (Hill & Petrucci, 2002). Chemical symbols, chemical formulae and chemical equations are examples of representations in chemistry.

2.2.3 The three levels of chemical representation of matter

Johnstone (1982, 1991) distinguished three levels of chemical representation of matter which are described as the macroscopic level, the submicroscopic level and the symbolic level.

In Johnstone's classification scheme, the macroscopic and sub-microscopic levels of representation of matter are in fact reality not a representation (see Figure 2.2). The submicroscopic level is as real as the macroscopic level. It is just the scale that distinguishes it, and the fact that the submicroscopic level cannot be seen easily makes it difficult to accept it as real (Chittleborough, 2004). However, chemists are now able to observe atoms or molecules using a scanning tunneling microscope.

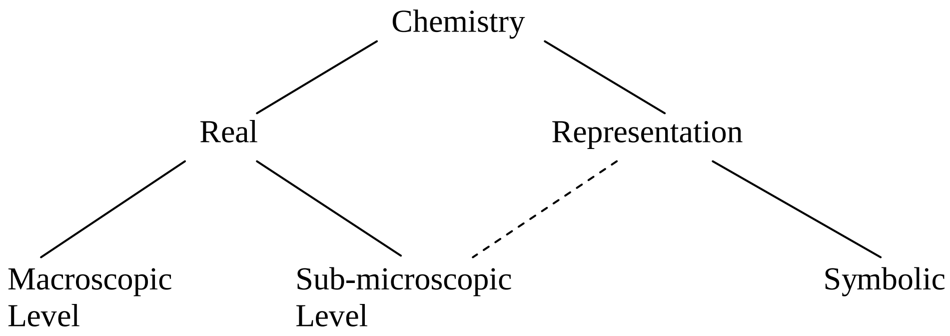


Figure 2.2: The relationship between the three levels of chemical representations and real and represented chemical data (Chittleborough, 2004, p.20, Figure 2.3)

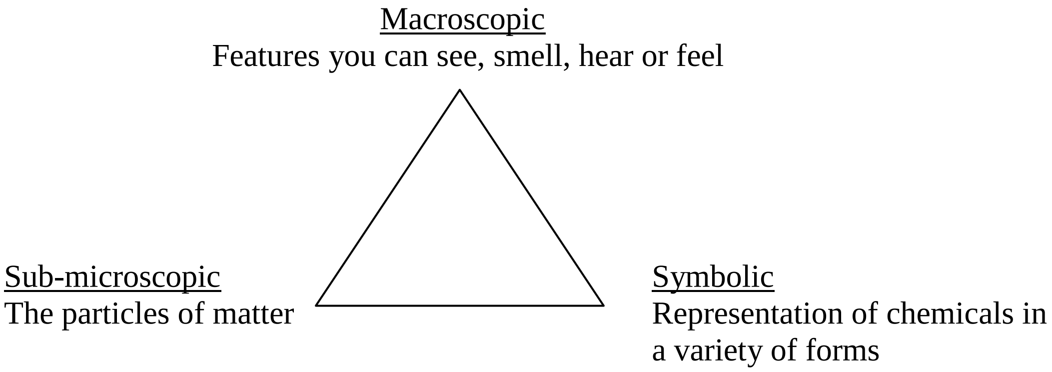


Figure 2.3: Three levels of chemical representation of matter (Johnstone, 1982)

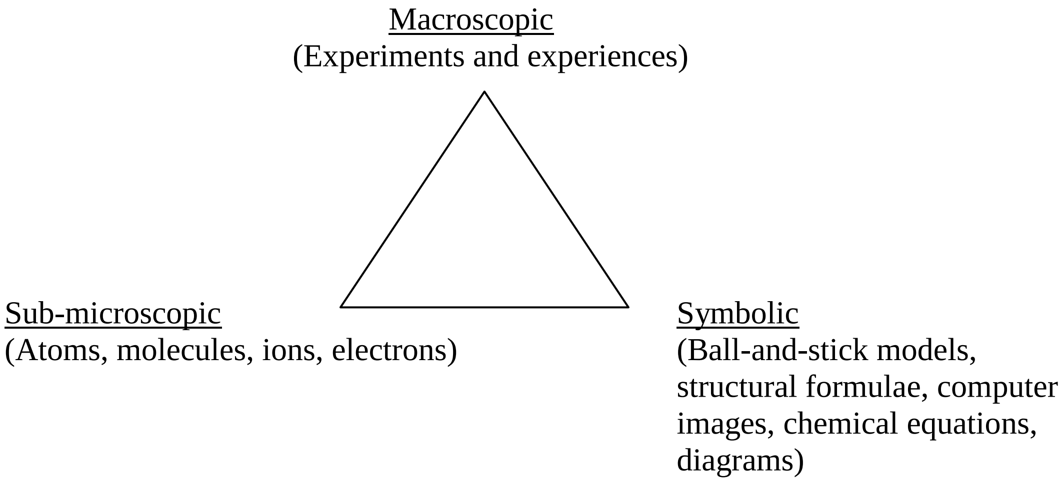


Figure 2.4: Examples of each of the 3 levels of chemical representation of matter

Figure 2.3 shows the three levels of chemical representation of matter while Figure 2.4 shows examples of each of the three levels.

Macroscopic representations describe bulk properties of tangible and visible phenomena in the everyday experiences of learners when observing changes in the properties of matter such as colour changes, formation of gases and precipitate in chemical reactions. Submicroscopic or molecular representations provide explanations at the particulate level, which can be used to describe the movement of electrons, atoms, molecules, and other particles. These submicroscopic entities are real but they are too small to be observed, so chemists describe their characteristics and behavior using symbolic representations to construct mental images. Symbolic or iconic representations involve the use of chemical symbols, formulae and equations, as well as molecular structures, drawings, diagrams, models, and computer animations to symbolize matter (Barak & Dori, 2005; Chandrasegaran, Treagust & Mocerino, 2007, 2009; Treagust et al., 2003).

Johnstone (1982) described the macroscopic as descriptive and functional, and the submicroscopic as representational and explanatory. All three levels of representations are integral in developing an understanding of the chemical concepts under investigation.

Research shows that many secondary school and college students, and even their teachers, have difficulty transferring from one level to another (Chittleborough & Treagust, 2007; Gabel, 1993, 1998; Sim, 2006; Yarroch, 1985). Such findings suggest there is a need to emphasize the difficulty of transferring between different types of representations within each level, as well as transferring from one level to another (Treagust & Chittleborough, 2001).

Johnstone (1997, p.263) proposes the gradual development of the three interconnected levels and warns against introducing all three levels simultaneously to beginning chemistry students because the working space of the brains cannot handle all three levels simultaneously.

2.2.4 The roles of representations in chemistry learning

> …representations help the students think through and explain their justifications for their ideas. They are learning to talk chemically by taking a position and using the representations to support their ideas. It is interesting to note that our preliminary analyses of students' representations and explanations showed that students were better able to explain more complex ideas when they reasoned with the help of representations as compared to reasoning without them. It is likely that aspects of the representations cue specific types of knowledge. (Coleman, undated, p.4)

In the field of chemistry as well as other sciences, chemical representations such as formulae, diagrams, equations, and graphs serve a profound role in the understanding and practices of chemists and other scientists, as well as students who are learning chemistry.

The daily practice of chemists depends heavily on the use of various representations to shape and understand the products of chemical investigations. For example, representations allow chemists to have a common language for their joint inquiry (Nye, 1993), and serve as tools to conduct scientific investigations and communicate with professional members within the scientific community (Kozma, Chin, Russell, & Marx, 2000). Representations, both those generated by scientists (such as diagrams and molecular structures) and those generated by their instruments (such as NMR and mass spectra), are among the physical systems historically constructed by the scientific community to support the understanding of chemical entities and processes (Schank & Kozma, 2002).

In professional journals, chemical representations such as symbols, formulae, equations, and structures, are routinely and extensively used to describe and explain chemical reactions and phenomena. Hence, being familiar with these representations and their usage in chemistry is essential for the acquisition of expertise (Kozma & Russell, 1997; Kozma et al., 2000).

The use of chemical representations is also an inseparable part of the study of chemistry. Learning is dependent on clear explanations. Chemical explanations rely on students' understanding of the role and purpose of chemical representations. Thus, chemical representations play a significant role in providing explanations of abstract concepts. Representations, whether they are in the form of symbols, models, diagrams, or graphs, provide a perceptual accessibility or a framework to help students visualize the particles of the microscopic world. For example, chemical representations such as ball-and-stick models and chemical equations are visible and tangible and therefore provide students with a more concrete perception of what happens to atoms and molecules during a chemical reaction (Heitzman & Krajcik, 2005). Pictorial drawings or submicroscopic representations are used to convey entities and states, such as characteristics of elements, compounds, and mixtures, or of liquids, solids, and gases (Schank & Kozma, 2002). Animations illustrate processes such as electrolysis.

Chittleborough (2007) pointed out that representations transverse the language barrier. Chemistry textbooks may be written in various languages but often reveal common diagrams and pictures. Even if the readers are unable to read the written language, they can interpret these diagrams. These diagrams and pictures thus become powerful explanatory tools that transverse the language barriers. In teaching chemistry, a multi-modal approach is commonly used whereby the spoken and written language contributes to explanations of chemical concepts alongside experiments, diagrams, pictures and models. Students who are learning chemistry in a language that is not their first language are perhaps more dependent on using chemical representations to understand concepts in order to compensate for any shortcomings in language. In this situation, representations play an important role in complementing the learning of abstract concepts.

2.2.5 Chemists' versus students' uses of representations

The various ways that expert chemists visualize chemical entities and processes differ significantly from the ways novice chemistry students use representations. They differ both in their laboratory practices and in their ability to use and understand various forms of representations.

In an ethnographic study of professional chemists in an academic and a pharmaceutical chemistry laboratory, both focusing on the synthesis of new compounds, Kozma, Chin, Russell, and Marx (2000) noticed that representations such as structural diagrams, equations, instrument-generated displays were everywhere in their chemistry laboratories.

Other findings from this study included: (i) chemists moved seamlessly across different representations and used them together to understand phenomena under investigation, (ii) chemists coordinated the material affordances of representations within and across representations to think about and understand their investigations, and (iii) they used the social affordances of these features to argue for, explain and justify their findings.

Several other patterns in representational practices were also noted. These included: (i) chemists used different representations for different purposes, (ii) chemists used multiple representations together to construct an understanding of the chemical phenomena they investigated in their experiments, (iii) chemists used structural diagrams to describe the composition and geometry of the compounds that they were trying to synthesize, (iv) they used diagrams and chemical equations to reason about the reaction mechanisms needed to transform reagents into products and the physical processes that would support these transformations, (v) chemists analyzed various instrumental displays and printouts to verify the composition and structure of the compounds that they were trying to synthesized, (vi) as they worked together to understand the results of their investigations, chemists made references to specific features of the printouts (for example, peaks on NMR or mass spectra) as warrants for claims that the desired products were obtained.

Through the use of structural diagrams, equations, and instrumental printouts, chemists are able to visualize, discuss, and understand the molecules and chemical processes that account for the more perceivable substances and phenomena they observed in the laboratory.

In an observational study of an organic chemistry course, Kozma (2000b, 2003) examined the laboratory practices of college students. It was observed that there was infrequent use of representations by students during their wet laboratory experiments. Students rarely discussed the molecular nature of the reactions that they were running on the laboratory bench. Their practices and discussions were focused exclusively on the physical aspects of their experiments such as setting equipment, trouble shooting procedural problems, and interacting with the physical properties of the reagents they were using. In the discussions between students and their instructors, the mention of molecular properties and processes was absent. In general, there was a lack of representational use.

However, in a subsequent session in the computer laboratory, when these same students worked together while using a molecular modeling software program that allowed them to build, examine, and manipulate representations of the same compound that they synthesized in the previous wet lab session, student discourse was filled with references to the molecular properties and processes that underlie the chemical synthesis that they previously performed in the wet lab.

Scientists such as chemists are very skilled at flexibly and fluidly moving across multiple representations based on underlying principles. They used the features of various representations, individually and together, to think about the goals and strategies of their investigations and to negotiate a shared understanding of underlying entities and processes (Kozma, 2000a). Novices are less skilled in the use of representations and rely on their surface features for meaning. The students had difficulty making connections between representations and phenomena they stand for and making connections across the features of multiple representations to understand scientific phenomena in terms of underlying entities and principles. Nonetheless, the use of certain representations such as molecular models with features that correspond to underlying entities and structures increase students discourse above substantive chemistry (Kozma, 2003).

2.3 Alternative Conceptions in Chemistry

Although everyday chemical events (macroscopic) such as heating, combustion, solids, liquids and gases changing phase and, melting and boiling also includes submicroscopic and symbolic representations, many students only experience these phenomena at the sensory level without understanding the chemistry behind all these changes. The confusion between the macroscopic and submicroscopic nature of matter is well documented (Anderson, 1990), and gives rise to students confusing chemical phenomena such as: (i) dissolving and melting, (ii) having difficulty accepting the conservation of matter and mass when some substances appears to disappear, (iii) accepting the “disappearance” of liquids during evaporation, (iv) believing that if a gas is formed then it changes into air.

The particulate nature of matter forms the foundation of all chemical explanations and it is often assumed that students accept and understand the concept of the particulate nature of matter (Chittleborough, 2004). However, the particles of matter remain a problematic area in chemistry. Students tend to associate elements with atoms and molecules with compounds (Fensham, 1994). More recent studies found similar confusion still persists among students, even at the tertiary level (Chittleborough & Treagust, 2007; Stains & Talanquer, 2007).

On the meaning of `particle’, Franco (2005) commented that when students talk about particles, they are often speaking of something completely different to what the teacher is talking about. They are actually talking about “small pieces of matter” (see Figures 2.5 and 2.6), which is different from the scientific conception.

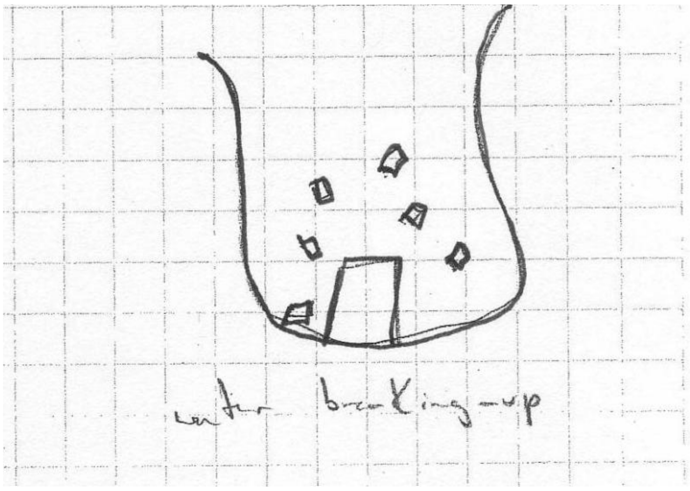


Figure 2.5: A sugar crystal being broken down by water (Franco, 2005, p.10)

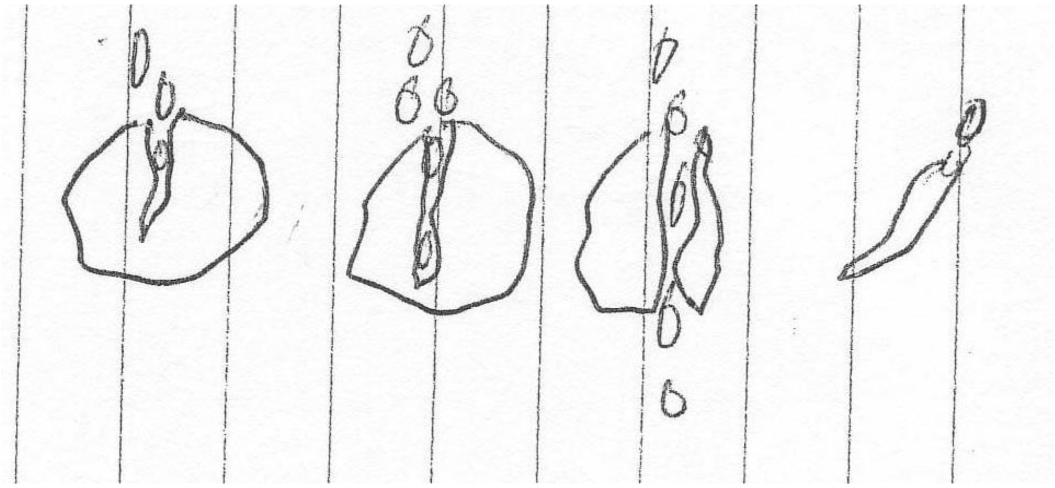


Figure 2.6: Sugar being broken down by water (Franco, 2005, p.10)

Franco (2005) believed that if students are not given enough opportunities to think about particles and particle properties, they probably will keep attributing macroscopic properties to particles.

On physical change and chemical change, Gabel (2000) obtained data from 270 prospective chemistry elementary teachers, of which 99% had a one year course in high school chemistry. Many college students think that when dry ice changes to a vapour, this is a chemical rather than a physical change (33%). Given a group of equations representing chemical reactions that include ones that show oxygen combining with both carbon and methane, only 33% think that both equations represent burning (National Research Coucil, 1996). Chandrasegaran, Treagust, and Mocerino (2007) use a 15-item, two-tier multiple-choice diagnostic instrument and identified 14 conceptions related to chemical reactions that indicated: (i) confusion between macroscopic and submicroscopic representations, (ii) a tendency to extrapolate bulk macroscopic properties of substances to the submicroscopic level, and (iii) limited understanding of the symbolic representational system.

Bodner (1987) found that some students enrolled in the chemistry graduate program at Purdue University and who had completed undergraduate chemistry majors at other institutions thought that the gas found in the bubbles of boiling water were hydrogen and oxygen rather than water vapour. Osbourne and Cosgrove (1983) who tested children from ages 12 to 17 found similar results.

Doctoral students enrolled in a science education research seminar at Indiana University also had misconceptions about fundamental chemical concepts. For example, when studying research on science misconceptions, students were asked whether toast burned or decomposed when it was overheated in a toaster. Most thought that it burned. Some students said they had never looked at toast while it was in the toaster and were not convinced of the reaction type until after they did so (Gabel, 2000). Unfortunately this kind of discussion usually does not take place in many chemistry classrooms or courses. Instead, chemistry is taught on the symbolic level using materials that are unfamiliar to students.

2.4 Representational Competence in Chemistry

> One can neither understand chemistry without using representations nor use representations of the domain without some understanding of chemistry. Consequently, representational competence is the complement of chemistry understanding, the first focusing on the activity of using representations and the second focusing on the resultant meaning construed from this activity (Michalchik, Rosenquist, Kozma, Kreikemeier, Schank, & Coppola, 2004).

Much of chemistry is untouchable and unobservable and relies on a system of representations to explain chemical phenomenon. In order to understand chemistry, students need to acquire a certain representational fluency or literacy. Students need to become competent at using and manipulating representations if they are to be able to move beyond the surface features of physical phenomena and rote manipulation of symbols. Coleman (undated) argued that this kind of behavior is necessary for students to increase their knowledge of chemistry, as well as to advance their understanding of the nature of scientific knowledge (that is, epistemic knowledge). According to Coleman (undated, p.8), gaining practice of representational use will help students see how models can be used to test ideas or to understand that knowledge can be treated as on object of inquiry and not served as a fact to be memorized (Coleman, undated, p.8).

2.4.1 Distinguishing and defining the terminologies

Defining the term “Representational competence” is problematic. One reason for this difficulty is that the term “Representational competence” is not used consistently in the literature.

Kozma and Russell (1997) used the term “Representational competence” to describe a set of skills and practices that allow a person to reflectively use a variety of representations or visualizations, singly and together, to think about, communicate, and act on chemical phenomena in terms of underlying, aperceptual physical entities and processes (Kozma, 2000a, 2000b). According to Kozma and Russell (1997), these representational skills include: (i) abilities to use representations to generate explanations, (ii) fluently translate one representation into another, (iii) make connections between representations and concepts.

It should be noticed that the definition of representational competence and the dimensions of representational skills differ among researchers, and even the same researchers in different studies.

For example: Wu (2003) adopted the same definition used by Kozma and Russell (1997) and Kozma et al. (2000) who argued that representational competencies included generating representations purposely, using representations to make explanations, using representations in a social context to communicate understandings, and making links across representations. However, in an article entitled "*Multimedia Learning in Chemistry*", Schank and Kozma (2002, p.18) merely referred to representational competence as "skills in using representations" while in another study entitled "*Learning Chemistry Through the Use of a Representation-Based Knowledge Building Environment*", the same authors (Schank and Kozma, 2002, p.24) defined representational competence as "ability to create and analyze representations".

In "*Students Becoming Chemists: Developing Representational Competence*", Kozma and Russell (2005) suggested seven skills that might constitute the core of a substantive curriculum of representational competence in chemistry. These included:

i. The ability to use representations to describe observable chemical phenomena in terms of underlying molecular entities and processes.
ii. The ability to generate or select a representation and explain why it is appropriate for a particular purpose.
iii. The ability to use words to identify and analyze features of a particular representation (such as a peak on a coordinate graph) and patterns of features (such as the behavior of molecules in an animation).
iv. The ability to describe how different representations might say the same thing in different ways and explain how one representation might say something different or something that cannot be said with another.
v. The ability to make connections across different representations, to map features of one type of representation onto those of another (such as mapping

a peak of a graph onto a structural diagram), and to explain the relationship between them.

vi. The ability to make the epistemological position that representations correspond to but are distinct from the phenomena that are observed.

vii. The ability to use representations and their features in social situations as evidence to support claims, draw inferences, and make predictions about observable chemical phenomena.

A review of literature in chemical education research also shows that besides the term “representational competence”, several other terms such as “representational fluency”, “chemical visualization skills”, and “modeling ability” have been used by other researchers, apparently to refer to the same meaning.

For example, “representational competence” is also referred to as “chemical visualization skills” (Russell & Kozma, 2005). These skills include the ability to utilize chemical symbols, chemical equations, various types of structural diagrams, diverse graphical formats such as spectral plots and computer models, and nanoscale animations as appropriate for solutions of problems or tasks and the investigation and understanding of phenomena and concepts. In their article “Assessing Learning from the Use of Multimedia Chemical Visualization Software”, they used the term “Chemical visualization skills” and “representational Competence” interchangeably.

In the article “*Chemsense*: *Developing representational fluency in chemistry*”, Coleman (undated) used the term representational fluency instead of representational competence, where representational fluency means the ability to move fluidly among different representations. According to Coleman, students’ representational fluency would be indicated by their ability to:

i. See representations as corresponding in some way to ideas that explain phenomena.
ii. Identify and analyze features of a representation (such as a peak on a graph) and use them to explain, draw inferences, and make predictions about chemical phenomena or concepts.
iii. Generate their own representations or select a different representation or a set of representations for different purposes.
iv. Link chemical phenomena at the observable, physical level with an understanding of chemistry at the particulate level.
v. Move fluidly back and forth among chemical representations at both the macroscopic and microscopic levels.
vi. Evaluate representations and identify what they represent and fail to represent.

(Coleman, undated, p.4)

The term "representational fluency" is also used by Stieff and McCombs (2006) in their article entitled "*Increasing Representational Fluency with Visualization Tools*". According to them, representational fluency in chemistry includes skills such as use of accepted chemical representations and reasoning from submicroscopic perspectives.

In their study on the modeling ability of non-major chemistry students and their understanding of the submicroscopic level, Chittleborough and Treagust (2007) used the term "modeling ability" to refer to "representational competence".

For the purpose of this study, the term "representational competence" shall be used. See Chapter 1 - Section 1.7 for the operational definition of this term.

2.4.2 Representational skills of expert and novices

A long history of research in cognitive psychology compared experts and novices to document similarities and differences in their cognitive structures and processes (Glaser & Chi, 1988). A common finding is that generally experts are able to cluster apparently dissimilar problems or situations into large meaningful clusters based on underlying concepts and principles. For example, significant differences have been found in the cognitive structures of experts and novices in physics (Chi, Feltovich & Glaser, 1981; Larkin, 1983; cited in Kozma, 2003). In one task, expert physicists create large meaningful clusters of text book physics problems based on underlying physics principles, such as “force problems” or “energy problems”. Novices organize their groups based on surface features, such as “pulley problems” or “inclined plane problems”.

In an experimental research, Kozma and Russell (1997) compared 11 professional chemists, faculty members, and graduate chemistry students (i.e. experts) and 10 college students taking general chemistry (i.e. novices) on two multimedia tasks.

In the first task (a sorting task), subjects were shown 14 different computer displays corresponding to several chemical reactions. The representation included: (i) video segments of experiments, (ii) molecular-level animations, (iii) dynamic graphs of physical property of the system, (iv) chemical formulae or equations. Subjects were then given a set of 14 cards corresponding to each representation and were asked to sort these cards into meaningful subsets. The expert chemists were able to create large, chemically-meaningful clusters, significantly more so than novices. Chemists also used conceptual terms to label their clusters, terms such as “gas laws,”, “collision theory,” and so on. In addition, chemists tended to use a greater variety of representations in their groupings, 3 or 4 different kinds of representations compared with only 1 or 2 different types used by novices (for example, only graphs, or graphs and animations). Chemistry students labeled their groups using terms that merely described the surface features of the groups (for example, “molecules moving about”, “concentrations changing with time”).

In the second task (a transformation task), subjects were shown various representations (the same as those in the first task) of chemical phenomena presented in one form. They were asked to describe what they saw and then to transform each representation into various other forms as specified. For example, transform an animation into a corresponding graph, a video of a reaction into an equation. It was found that experts were significantly better than novices at transforming a given representation into a chemically meaningful representation in another form. They were particularly more skillful than novices at providing verbal description or transformation for a representation given in any form. While chemists were more likely to give a description based on the underlying concepts and principles (for example, “heating shifts the equilibrium shown by colour change,”), novices were more likely to merely describe what they saw (for example, “heating causes the colour change to get darker,”). Chemists were also much better than novices for transformation that required a constructed response such as drawing graphs or writing chemical equations. However, they were only slightly better than novices with transformations requiring only a choice between answers. For example, to match a given equation to one of several video segments, since surface features could be utilized to make a choice.

In general, novices used the surface features such as colour, motion and label of the display to try to build an understanding of the chemical phenomena they represented. However, these features constrained their understanding. Unlike chemists, students were unable to move fluidly across the boundaries of different representations and connect them to create an understanding that went beyond the surface features of a given representational type. On the contrary, chemists were able to see displays with different surface features as all representing the same principle, concept, or chemical situation, and they were able to transform representations of a chemical concept or situation in one form into a different form. They easily moved across different representations and used them together to express their understanding of chemical phenomena.

2.4.3 Students' conceptions of chemical representations and their representational competence

Chemical representations have a dual nature – visual and conceptual (Wu & Shah, 2004). Students' conceptual errors and difficulties understanding and using visual representations in chemistry (Ben-Zvi et al., 1987, 1988; Griffith & Preston, 1992; Heitzman & Krajcik, 2005; Keig & Rubba (1993); Kozma & Russell, 1997; Wu & Shah, 2004; Yarroch, 1985) further suggest that chemical representations are not just visual diagrams but are conceptual constructs as well (Hoffmann & Laszlo, 1991).

Wu, Krajcik and Soloway (2001) believed that visualizing chemical representations require the cognitive linkages between conceptual components that involve substantial content knowledge of underlying concepts, and visual components that involve encoding and interpreting the symbols and conventions.

Wu and Shah (2004) suggest incorporating a visuo-spatial thinking approach in teaching chemistry as this approach emphasizes a close interaction between visual representations and relevant concepts. As most visual representations include features that correspond to conceptual entities, they could be used to scaffold students' learning of concepts.

Apart from a study on "Representational competence and chemical understanding in the high school chemistry classroom" by Michalchik, Rosenquist, Kozma, Kreikemeier, Schank and Coppola (2004), there is no quantitative study on the relationship between students' representational competence and their conceptual knowledge in chemistry. Nevertheless, the above studies indeed suggest a possible relationship between students' skills in understanding and using representations, or representational competence and their conceptual knowledge in chemistry.

2.4.4 Students' difficulties in using representations of chemical concepts

Although symbolic and microscopic representations are frequently used in many chemistry textbooks, applying ideas of particles and constructing microscopic representations to make explanations of observations are very difficult for many secondary school students (Ben-Zvi, et al., 1987; Gabel, 1999; Griffith & Preston, 1992; Harrison & Treagust, 2000; Kozma, 2000a, 2000b; Kozma & Russell, 1997, Krajcik, 1991; Wu, 2002; Wu, Krajcik, & Soloway, 2001; Wu & Shah, 2004).

Research in students' use of representations in chemistry identified 3 types of students' difficulties. These difficulties are: (i) comprehending and interpreting representations, (ii) translating or moving between the 3 levels of representations, and (iii) transforming between 2-D and 3-D representations.

2.4.4.1 Difficulties in comprehending and interpreting representations

According to Wu and Shah (2004), three major alternative conceptions that arise from difficulties comprehending and interpreting representations are:

(i) Representing chemical concepts or phenomena at the macroscopic level rather than the microscopic or symbolic level

Students at the secondary school level are unable to connect chemical representations to the macro-scale phenomena.

In Krajcik (1989), seventeen 9th graders were interviewed and asked to draw and describe how the air in a flask would appear if they could see it through a very powerful magnifying glass. Only three of them drew air composed of tiny particles, while others held a continuous view of matter and represented the air by wavy lines or a vapor model.

(ii) Comprehending visual representations at the macroscopic level and by their surface features

A second alternative conception is demonstrated by secondary school students as well as college students when they were asked to interpret microscopic and symbolic representations (Garnett, Garnett & Hackling, 1995; Kozma & Russell, 1997; Krajcik, 1991). Many students have difficulty representing chemical concepts at the microscopic or symbolic levels (Ben-Zvi, Eylon, & Silberstein, 1988; Krajcik, 1989).

Ben-Zvi et al., (1988) explored the levels of descriptions generated by high school students, when they were asked to interpret the meanings of two symbolic representations: $H_2O(l)$ and $Cl_2(g)$. Although most of the students in the study were able to generate some macroscopic descriptions of water such as its properties, the microscopic representations they used to explain the phenomena were not appropriate.

Some students viewed $Cl_2(g)$ as a representation of one particle instead of a collection of multiple molecules, because they did not recognize that (g) represents chlorine molecules in a gas state and means a large amount of Cl_2 molecules.

By literally interpreting the chemical formula of water molecules, $H_2O(l)$, some students believed that a water molecule contains a unit of hydrogen gas, H_2. These students confused atoms with molecules, so they held a conception that a water molecule consists of another molecule, H_2. Ben-Zvi et al. (1988) also showed that many students, even after receiving substantial chemistry instruction, thought that formulae were merely abbreviations for names rather than a way to represent the composition or a structure.

(iii) Difficulties interpreting chemical equations or interpreting chemical reactions as a static process

Many students are unable to visualize the interactive and dynamic nature of chemical process by viewing symbols and equations (Ben-Zvi, et al., 1986, 1987; Krajcik, 1991).

Students interpreted an equation such as $C(s) + O_2(g) \rightarrow CO_2(g)$, as a composition of letters, numbers and lines instead of a process of bond formation and bond breaking. The technique of balancing chemical equations made students picture chemical equations as mathematical puzzles (Ben-Zvi et al., 1987), and they could even work algorithms without having a conceptual understanding of the phenomena (Yarroch, 1985). Thus, while chemists view a chemical reaction represented by an equation as an interactive and dynamic process, students can only construct a static model of it.

2.4.4.2 Difficulties in translating or moving between the three level of representations

By translating representations, we mean students interpret representations by obtaining appropriate information, and move among other representations of the same concept. Students move representations by either providing other representations to convey the same information, or by identifying the similar and different information that the representations depict (Heitzman & Krajcik, 2005).

Translating representations in chemistry involves thinking about phenomena in three levels: macroscopic, molecular and symbolic (Gabel, 1999; Johnstone, 1993, 1997). Further, within each level exists another dimension – dynamics, for change is the essence of chemistry. Yet many of our chemical representations of dynamic processes are static (Harrison & Treagust, 2002).

Moving among the three thinking levels and two dimensions makes the process of translating representations such as translating chemical equations, very difficult (Johnstone, 1993, 1997, 2000b, 2006). It is apparent that students would have difficulty when working with this complex task.

Several studies show that students' difficulties in navigating through chemical representations may intensify if (i) they are novices at using the representations, (ii) their understanding of chemical concepts are not yet coherent, and/or (iii) students have low visual-spatial abilities (Heitzman et al., 2004; Kozma, 2000a; Stieff, 2005; Wu, 2003; Wu, Krajcik, & Soloway, 2001).

Compared with chemists, students are less capable of providing equivalent representations for a given representation (Kozma and Russell, 1997). As in Keig and Rubba (1993), a large number of students were unable to make translations between chemical formula, electron configuration, ball-and-stick model. Students' performances on making translations were correlated to their understanding of underlying concepts. Keig and Rubba (1993) argued that making translation between representations is an information-processing task that requires understanding of the underlying concepts. In translating and transforming representations, Lesh, Post and Behr (1987) believed that conceptual knowledge allows students to interpret the information provided by the initial representation and infer the details to construct the target representation.

Students had difficulties determining molecular structures when empirical formulae were given (Wu & Shah, 2004), and their performances on the translation of representations were not correlated to their visual-spatial ability but their conceptual understanding about the representations.

2.4.4.3 Mental transformation between 2-D and 3-D representations

Based upon a hypotheses that a logical process to transform or mentally manipulate 3-D representations was through a step-by-step approach, Tuckey, Selvaratnam, and Bradley (1991) argued that students' difficulties were caused by either not using a stepwise approach, or unable to finish one or more steps.

Many students are not able to form 3-D mental images by viewing and visualizing 2-D chemical structures and mentally rotate 3-D images (Shubbar, 1990; Tuckey, Selvaratnam & Bradley, 1991).

In order to successfully create a 3-D image by viewing a 2-D diagram, students are required to decode the visual information provided by depth cues used in the diagram (Shubbar, 1990). These depth cues include the foreshortening of lines, relative sizes of different parts of the structure, representations of angles, and the extent to which different parts of the diagram overlap.

Tuckey, Selvaratnam, and Bradley (1991) found that some students cannot correctly identify depth cues, and even if they can, they may not be able to mentally track how depth cues change as a result of rotation (Shubbar, 1990). This makes mentally rotating chemical structures extremely difficult for students.

2.4.5 Assessing representational competence: Past methodologies

In an experimental study to examine how professional chemists (experts) and undergraduate chemistry students (novices) respond to a variety of representations, two experiments were carried out (Kozma & Russell, 1997). In the first experiment (a sorting task), subjects were provided with a range of representations and asked to grouped them together in any way that make sense. In the second experiment (a transformation task), subjects were asked to transform a range of representations into specified alternative representations.

In a case study, Hinton and Nakhleh (1999) examined the mental representations of chemical reactions used by six students in a college freshman chemistry class at a large university in structured interviews and categorized the representations expressed by the students as microscopic, macroscopic, or symbolic representations of chemical reactions.

In their historical and observational study, Kozma, Chin, Russell, and Marx (2000) examined the historical origins and contemporary practices of representation use in chemistry. They examined representations spontaneously generated by chemists, as well as those generated by their tools or instruments, and looked at how scientists individually and collaboratively, coordinate these two types of representations with the material substances of their investigations to understand the structures and processes underlying their scientific investigations. They also described how scientists use representations and tools in the chemistry laboratory.

Coleman (undated) conducted a series of interviews to find out how well chemistry students used visual representations. Student pairs from local high schools were encouraged to “think aloud”, to work together, and to make use of tools for creating representations as they explained chemistry problems. These tools were provided on the tables before them, specifically: (i) paper and pens, (ii) molecular modeling kits, (iii) other items for creating 3-D molecules (such as toothpicks, marsh mallows, round-shaped candies). Evidence of students’ representational competence (Kozma & Russell, 1997) in their discourse and manipulations of representations were observed. In their interviews of students’ reasoning with chemical representations, examples of three of the characteristics of representational competence have been identified. These were: (i) using representations as part of their justifications, (ii) focusing on particular aspects of the representations, (iii) moving fluidly among different representations.

In a study to explore the effects of a computer-based learning environment on high school students’ efforts to collaboratively represent chemistry concepts during an instructional unit on solubility, Michalchik, Rosenquist, Kozma, Kreikemeier, Schank, and Coppola (2004) used a quantitative analysis of pre-test and post-test data to locate chemistry concepts for which student representations seemed to be most clearly affected by their use of representational tools within the ChemSense environment.

Kozma and Russell (2005) proposed a conceptual structure of skills or representational competence which corresponds to a developmental trajectory that generally moves from the use of surface features to define phenomena which is characteristic of novices within a domain (Chi, Feltovich, & Glaser, 1981; Glaser & Chi, 1988; Kozma & Russell, 1997) to the rhetorical use of representations, which is characteristic of expert behavior (Kozma et al., 2000). The five representational competence levels are: Level 1: Representation as depiction; Level 2: Early symbolic skills; Level 3: Syntactic use of formal representation; Level 4: Semantic use of formal representation; Level 5: Reflective, rhetorical use of representations. See Table 2.1.

Russell and Kozma (2005) provided a more detailed picture of how representational competence can be assessed. Using the five representational levels suggested by Kozma and Russell (2005) as scoring rubric, a test item was presented as an example and the scoring of student's representational competence was worked through. To allow students the opportunity to show their understanding of a solubility-related process and represent it accordingly, a four-step "storyboard" question was given. Students were asked to draw and explain at the submicroscopic level how sodium chloride dissolves in water over time. Students were scored on both their chemical understanding as well as their representational competence. However, only the pre-test and post-test responses for representational competence were compared. See Figure 2.7.

Table 2.1
Summary of Representational Competence Levels
(Kozma & Russell, 2005, in J. Gilbert, 2005, pp.132-133)

Level 1: Representation as Depiction

When asked to represent a physical phenomenon, the person generates representations of the phenomenon based only on its physical features. That is, the representation is an isomorphic, iconic depiction of the phenomenon at a point in time.

Level 2: Early Symbolic Skills

When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on its physical features but also includes some symbolic elements to accommodate the limitations of the medium (e.g., use of symbolic elements such as arrows to represent dynamic notions, such as time or motion or an observable cause, in a static medium, such as paper). The person may be familiar with a formal representational system but its use is merely a literal reading of a representation’s surface features without regard to syntax and semantics.

Level 3: Syntactic Use of Formal Representations

When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on both observed physical features and unobserved, underlying entities or processes (such as an unobserved cause), even though the representational system may be invented and idiosyncratic and the represented entities or processes may not be scientifically accurate. The person is able to correctly use formal representations but focuses on the syntax of use, rather than the meaning of
the representation. Similarly, the person makes connections across two different representations of the same phenomenon based only on syntactic rules or shared surface features, rather than the shared, underlying meaning of the different representations and their features.

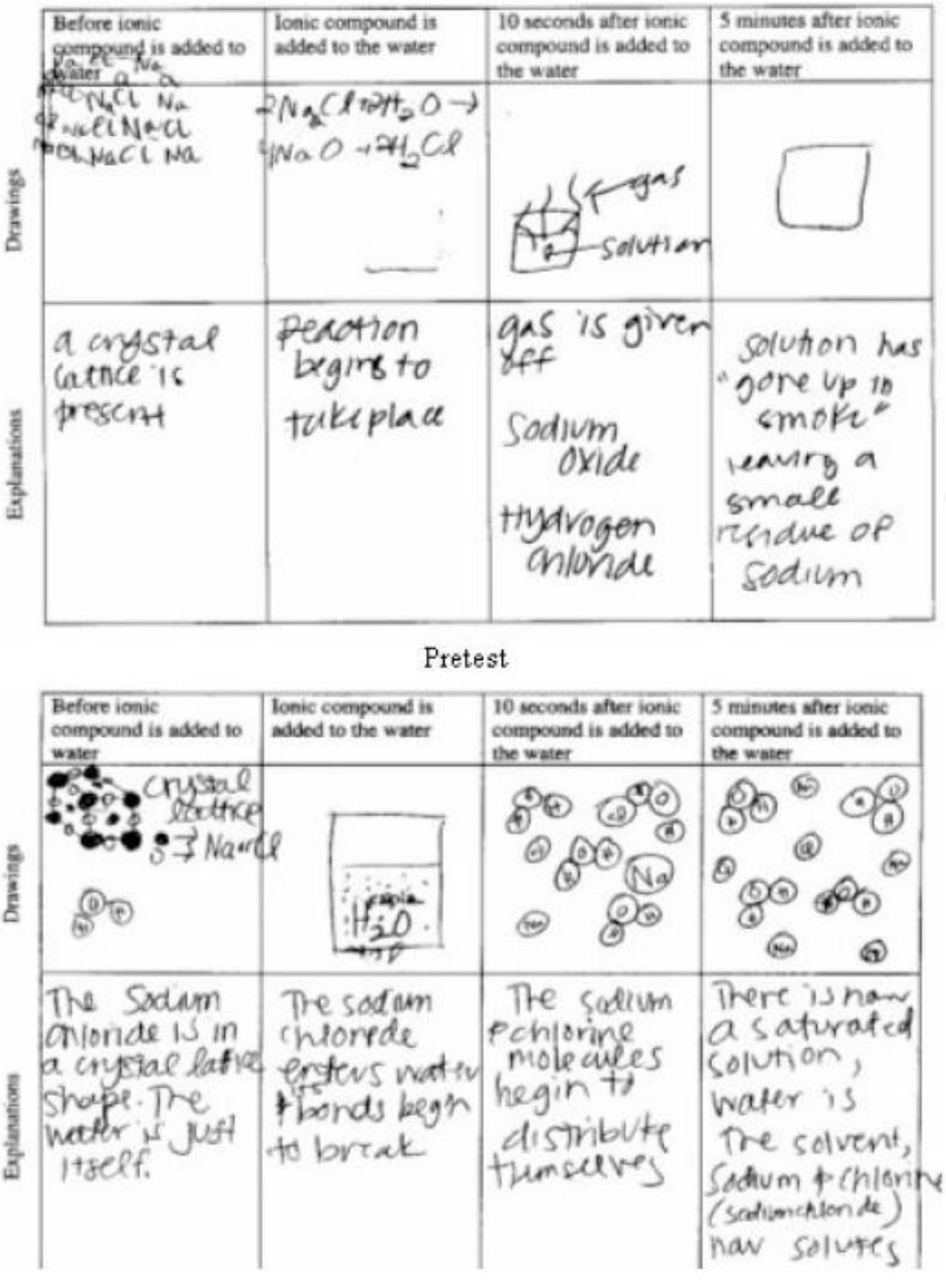
Level 4: Semantic Use of Formal Representations

When asked to represent a physical phenomenon, the person correctly uses a formal symbol system to represent underlying, non-observable entities and processes. The person is able to use a formal representational system based on both syntactic rules and meaning, relative to some physical phenomenon that it represents. The person is able to make connections across two different representations or transform one representation to another based on the shared meaning of the different representations and their features. The person can provide a common underlying meaning for several kinds of superficially different representations and transform any given representation into an equivalent representation in another form. The person spontaneously uses representations to explain a phenomenon, solve a problem, or make a prediction.

Level 5: Reflective, Rhetorical Use of Representations

When asked to explain a physical phenomenon, the person uses one or more representations to explain the relationship between physical properties and underlying entities and processes. The person can use specific features of the representation to warrant claims within a social, rhetorical context. He or she can select or construct the representation most appropriate for a particular situation and explain why that representation is more appropriate than another. The person is able to take the epistemological position that we are not able to directly experience certain phenomena and these can be understood only through their representations. Consequently, this understanding is open to interpretation and confidence in an interpretation is increased to the extent that representations can be made to correspond to each other in important ways and these arguments are compelling to others within the community.

A sample of the pretest and posttest responses for example test item is shown in Figure 2.7.



	Before ionic compound is added to water	Ionic compound is added to the water	10 seconds after ionic compound is added to the water	5 minutes after ionic compound is added to the water
Drawings	NaCl Na NaCl NaCl NaCl NaCl Na	$2Na_2Cl + 2H_2O \rightarrow$ $4NaO + 2H_2Cl$	gas solution	
Explanations	a crystal lattice is present	Reaction begins to take place	gas is given off Sodium oxide Hydrogen chloride	solution has "gone up in smoke" leaving a small residue of sodium

Pretest

	Before ionic compound is added to water	Ionic compound is added to the water	10 seconds after ionic compound is added to the water	5 minutes after ionic compound is added to the water
Drawings	crystal lattice NaCl	H_2O	Na	
Explanations	The Sodium chloride is in a crystal lattice shape. The water is just itself.	The sodium chloride enters water & its bonds begin to break	The sodium & chlorine molecules begin to distribute themselves	There is now a saturated solution, water is the solvent, Sodium & chlorine (sodium chloride) now solutes

Figure -12. Sample pretest (upper) and posttest (lower) for student using ChemSense.

Figure 2.7: Sample pre-test and post-test for student using ChemSense
(Russell & Kozma, 2005, p.30, Figure 12)

In the example, the student completed all frames of the storyboard but merely provided a macroscopic-level drawing of the solution, with a representation of the ionic lattice using the symbols “Na” and “Cl”. This provides evidence that the student is operating at a “surface level” representational competence, with discussion only on the observable, macroscopic features. Since the student uses representations as depictions, the score for his/her response at pretest is at “Level 1”. However, the same student demonstrated a richer, more complex representation of the underlying process at posttest. Space filling molecules were used to represent the underlying, invisible entities and processes. An accurate description of the dissolving process was provided. By using these representations to explain the physical phenomena rather than simply depicting what may be seen, the student demonstrated a semantic and social use of formal representations and the score at posttest was at “Level 4”.

In assessing representational fluency via Connected Chemistry, learning outcomes were assessed via pre-and post-test measures (Stieff & McCombs, 2006). All students (n=188) from three high school classrooms completed the pre-test one day before and the post-test three days after instruction. The 10-item measure included a variety of items that asked students to (i) define relevant terms, (ii) classify different types of matter, and (iii) draw particle-level representations. Examples of items that required the generation of chemical representations were: (i) Item 7 - Draw a sub-microscopic picture of a heterogeneous mixture. Explain your drawing in words, (ii) Item 10 - Water can exist as both steam and ice. Draw a sub-microscopic picture of liquid water, steam and ice. Explain, in words, each of your drawings. Overall performance and improvement in representational fluency were addressed via use of sub-microscopic reasoning (explain in words) and accepted chemical representations (draw). Post-test score was used as a final outcome measure. The mean scores on pre-post test measures for each school and curriculum (n=92 for lecture and test, n=96 for Connected Chemistry) were compared. For reasoning with sub-microscopic representations, total students using sub-microscopic representations on item 7 and item 10 were compared. For accepted chemical representations, student use of accepted chemical representations on item 7 and item 10 were compared.

Chittleborough and Treagust (2007) used a series of case studies to examine the modeling ability of first year non-major chemistry students and their understanding of the sub-microscopic level. Quantitative data sources included questionnaire and worksheets. Primary qualitative data were collected by interviews, observations, reflective journals, and students' laboratory reports. The data sources were processed, transcribed, collated and coded.

2.5 Possible Cognitive Variables Influencing Representational Competence

The choice of cognitive variables in this study is partly based on the fact that a number of researchers have been using all or some of these variables for many years as predictive variables for science learning, and partly based on the main theoretical framework for this study – information processing theory, as well as other cognitive learning theories (schema theory, Ausubel theory of meaningful learning and Piaget's theory of cognitive development) which form part of the theoretical framework of the proposed study. These cognitive variables are: (i) Formal reasoning ability or developmental level, (ii) working memory capacity, (iii) disembedding ability, (iv) prior knowledge, (v) learning orientations.

2.5.1 Working memory capacity

The concept of working memory refers to the human limited capacity system, which provides both information storage and processing functions (Atkinson & Shiffrin, 1968) and is necessary for complex cognitive tasks, such as learning, reasoning, language comprehension and problem solving. All information we wish to learn must be processed by the working memory before being permanently stored in the LTM.

Relevant to the influence of working memory is the work of Johnstone (1984, 1997, 2006), who observed a very sharp decline in students' success rates when the number of pieces of information needed to solve a chemistry problem was increased from five to six. Johnstone explained that the sudden decrease in success rate may occur when working memory capacity becomes overloaded. (see also Nagalingam, 2004).

However, in a number of cases, the Johnstone-El Banna model (Johnstone & El-Banna, 1986) may appear not to be in operation. Students may fail to achieve a task not because of lack of working memory, but for other reasons. Such failure does not violate the model, it just goes beyond the model (Johnstone, 2006; Johnstone & Al-Naeme, 1991). In addition, disembedding ability may have a effect in that low and, to a lesser extent, intermediate working memory students who are field dependent may experience a working memory overload, caused by irrelevant information or `noise' (Johnstone & Al-Naeme, 1991).

Numerous authors claim a link between working memory capacity and learning success, mainly in the area of problem solving in chemistry (Johnstone, 1984, 1997, 2006; Johnstone & Al-Naeme, 1991; Johnstone & El-Banna, 1986; Nagalingam, 2004; Niaz, 1996).

So far, a wide literature search conducted by the researcher did not uncover any study showing the influence of working memory capacity on novice chemistry students' representational competence in chemistry.

2.5.2 Prior knowledge

Prior knowledge is considered to describe the information stored in the LTM. The proposed IPM in this study, predominantly a top-down processing model, suggests that prior knowledge will influence the selection and the interpretation of incoming stimuli, and the consequent storage of information in the LTM.

In the chemical education research literature, the influence of prior knowledge on learning has been thoroughly studied and well documented (Boujaoude, 1992; Chandran, Treagust, & Tobin, 1987; Johnstone, 1997).

The importance of considering prior knowledge in the learning process has been stressed in a study by Prosser, Trigwell, Hazel & Waterhouse, 2000).

> This study confirms the vital role of prior knowledge and understanding in the quality of student learning outcomes… the key issue is to determine the nature of students' prior knowledge and understanding and to help students build an appropriate structure of prior knowledge so that students can focus on their studies in an integrated way… (Prosser et al., 2000, p.71).

Chemical education research also supports the notion that the extent of relevant prior knowledge has an effect on whether or not students adopt meaningful learning styles. Russell and Kozma (1997) suggested that lack of relevant prior knowledge may inhibit students' ability to make the links necessary for deep understanding of certain chemical phenomena. Prosser et al. (2000) demonstrated that prior knowledge influences a students' adopted approach to learning:

"Students with well developed prior knowledge are likely to be aware of those aspects of the context affording a deep approach, to adopt a deep approach and to have well developed post knowledge." (p.71)

2.5.3 Learning orientations

How a learner approaches learning has an impact on how meaningfully new information is stored in the LTM. Squire and Kandel (1999, p.71) pointed out that “the extent to which we can organize (what is perceived) and relate it to knowledge that we already have” influences “the nature and the extent of the encoding that occurs at the time of the initial learning.” Furthermore, “when encoding is elaborate and deep, memory is much better than when encoding is limited and superficial”.

Students may be considered meaningful learners or deep learners or rote learners or surface learners, in relation to a particular subject or topic or learning task. Prosser et al. (2000) believed that whether a student adopts a deep or surface learning approach is a reaction to a particular learning environment, in order to cope with certain situations and tasks. This is also influenced by a student’s level of relevant background knowledge and level of interest in the task (Ramsden, 2002).

Deep learners (Biggs, 1987; Prosser et al., 2000; Ramsden, 2002) are characterized by their attempts to bring meaning and personal understanding to new information. They try to relate new ideas to previous knowledge and relate concepts to everyday experiences. On the other hand, surface learners (Biggs, 1987; Prosser et al., 2000; Ramsden, 2002) restrict to learning to the minimum required to pass. They approach learning passively and perceive learning to be the rote memorization of information, in order to reproduce it in examinations. They rarely attempt to understand or integrate the material.

A questionnaire – the Learning Approach Questionnaire (LAQ), could be administered to assess the extent to which students believe they engage in meaningful learning activities in chemistry, such as relating new material to old, compared to how often they adopted more surface learning strategies.

Because deep understanding relies on students' linking new information to knowledge that already exists in the LTM, deep learners should perform better on transfer tasks.

Various studies demonstrated a relationship between learning orientations and learning outcomes, with deep learning strategies promoting higher achievement on tasks requiring an understanding of the material (Boujaoude, 1992; 2004; Prosser et al., 2000).

2.5.4 Developmental level or formal reasoning ability

According to Herron (1978), Piaget's developmental level is one which actually refers to students' intellectual development and not to psychomotor development.

Having its basis in a well-described learning theory, the construct of formal thought offers the ability to suggest specific difficulties students face. Staver and Halsted (1985) cited Herron, outlining the capabilities and limits of students who use concrete reasoning patterns. Such students can make inferences which are direct explorations from observations, but they cannot make inferences which are "twice removed from observations". This second capability to Herron (1975) is part of formal reasoning which is a prerequisite for understanding chemical concepts.

Formal operational thought is the last stage of cognitive development as described by Piaget, in which `deduction no longer refer directly to perceived reality but to hypothetical statements' (Inhelder & Piaget, 1958). Also taken from Piaget's work is a series of reasoning patterns that would describe formal thought operations. Adey and Shayer (1994) grouped the reasoning patterns into three main categories.

In Piaget's theory, schemata are continually growing and developing rather than remaining fixed. Within Piagetian theory, the onset of formal thought would be characterized by the development of all the cognitive operations at about the same time (Lawson & Renner, 1975). Piaget's model of cognitive development indicates that by late adolescent (11 to 14 years), young adults should have reached the final stage of maturation (Vass, Schiller & Nappi, 2000).

Neo Piagetian theories of learning still incorporate formal thought ability as one of several critical cognitive factors important for problem solving in chemistry (Niaz, 1987, 1996; Tsaparlis, 2005).

An extensive body of knowledge exists concerning the nature and relevance of cognitive or developmental levels to science teaching and learning (Staver & Jack, 1988). Lawson and Renner (1975) showed that students at the concrete operational stage are unable to develop an understanding of formal concepts, and that students at the formal operational stage demonstrate an understanding of both formal and concrete concepts. Niaz and Robinson (1992) reported that the developmental level of students is the most consistent predictor of success when dealing with significant changes in the logical complexity of chemistry problems. The findings were later confirmed by Tsaparlis, Kousathana and Niaz (1998). They reported that developmental level played the dominant part on student performance. Formal reasoning ability influences students' performance in chemistry (Chandran, Treagust & Tobin, 1987; Lawson, 1979; Nagalingm, 2004; Niaz & Lawson, 1985). Abraham, Williamson and Westbrook (1994) found that formal reasoning ability accounts for the understanding of chemical concepts. Tsaparlis (2005) investigated the effects of several cognitive variables on student performance on several types of molecular equilibrium problems and found that developmental level in terms of formal thought ability was the most important predictor of success.

Several measures of formal thought have been developed, validated and utilized in the research literature. What these measures share is an attempt to approximate the original Piagetian interviews. However, emulating Piagetian interview is problematic, especially with large number of students, due to the time-intensive nature of the interview procedure. As a result, written examinations, in particular, have been constructed to replace these interviews.

The closest approximation to the interview procedure is Shayer and Adey's Science Reasoning Tasks (Shayer & Adey, 1981), in which students are asked to make written predictions before they witness demonstrations and then are asked to explain what they saw in each case.

2.5.5 Relationship between selected cognitive variables and chemistry learning

Research findings on the relationship between the selected variables and chemistry learning in Sections 2.5.1 to 2.5.4 show that more often than not, more than one variable can act together to influence the effect of chemistry learning.

Niaz and Lawson (1985) found that working memory overload plays an influential role in the failure of the inspection method for balancing chemical equations for complex redox equations. They found that formal reasoning ability also influences students' performance, but disembedding ability does not. Balancing chemical equation is an example of problem solving.

Chandran, Treagust and Tobin (1987) found that prior knowledge and formal reasoning ability play a significant role in students' achievement in chemistry, but working memory capacity and disembedding ability do not.

High school students' ability to translate between different kinds of representations in chemistry (Keig & Rubba, 1993) did not correlate with their spatial abilities, but their reasoning skills and prior knowledge. In Keig and Rubba (1993), only 19% of students were able to come up with an appropriate ball-and-stick model to complete the formula-to-model translation. Analysis of interview protocols indicated that the most common errors made by students were caused by a lack of content knowledge instead of an inability to manipulate information spatially. However, the sample size of n=42 high school students in Keig and Rubba (1993) is relatively small.

Abraham, Williamson, and Westbrook (1994) found formal reasoning ability accounts for the understanding of chemical concepts.

Tsaparlis (1997) conducted a critical analysis of the structural concepts of chemistry from the information processing theory, the Piagetian developmental perspectives, Ausubel's theory of meaningful learning, and the alternative conceptions movements. He concluded that the different perspectives were related.

Demerouti, Kousathana, and Tsaparlis (2004) examined the effect of developmental level and disembedding ability on 12th grade students' conceptual understanding and problem solving ability in the area of acid-base equilibria. It was found that both variables played an important role in student performance, with disembedding ability clearly having the larger effect. Developmental level was connected with most cases of concept understanding and application, but less so with situations involving complex conceptual situation and/or chemical calculations. On the other hand, disembedding ability was involved in situations that required conceptual understanding alone, or in combination with chemical calculations.

Boujaoude et al. (2004) investigated the relationship between students' performance on conceptual and algorithmic chemistry problems with a number of selected cognitive variables, namely: learning orientations, formal reasoning ability or developmental level, and mental capacity, but not with disembedding ability. The problems were on chemical change, chemical equations, gas laws, limiting reagents, and redox equations. The three cognitive variables were significant predictors for success with conceptual problems, but not algorithmic problems.

Findings from the above studies are on chemistry learning in general. The relationships between the various cognitive variables with problem solving are also not conclusive. Further research is necessary.

2.6 Chapter Summary

Numerous research findings show multiple levels of representation of chemical concepts, multiple representations, the abstract nature of chemistry, alternative conceptions, as well as the language of chemistry contribute to learning difficulties in chemistry.

From the history of chemical representations right up to the present, representations have always been an integral part of chemistry. As chemistry is a language, representations are the tools of communication. However, there is no quantitative study on beginning chemistry students' understanding of chemical representations. Studies on representational competence also tend to relate more to expert chemists and advanced chemistry learners. Relatively little research interest was devoted to beginning chemistry students. Besides, most of these studies used qualitative methods with small sample sizes and findings are not generalizeable.

Although there have been numerous studies on the influence of various cognitive variables on chemistry learning, there is no study that specifically examines the influence of prior knowledge, developmental level, working memory capacity, and learning orientations on students’ representational competence in chemistry.

This study therefore seeks to investigate Form four students’ representational competence of basic chemical concepts using a mix of quantitative and qualitative techniques. The influence of selected cognitive variables on their representational competence was also examined.

In Chapter 3, conceptualization of the study will be described.