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RESEARCH REPORT (EMPIRICAL STUDY)
Assessement

Tami LEVY NAHUM, Avi HOFSTEIN, Rachel MAMLOK-NAAMAN, and Ziva BAR-DOV
The Weizmann Institute of Science, Department of Science Teaching (Israel)

CAN FINAL EXAMINATIONS AMPLIFY STUDENTS' MISCONCEPTIONS IN CHEMISTRY?

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ABSTRACT: Many researches have been conducted in order to examine students' misconceptions in chemistry. The present study focuses on students' difficulties regarding the concepts *chemical structure and bonding*, which are essential for understanding many concepts and topics in chemistry. Research conducted around the world has clearly shown that the concepts associated with *chemical structure and bonding*, such as molecules, ions, hydrogen bonds, and giant lattices are abstract and are highly based on the sub-microscopic nature of chemistry. In Israel, the central developed Matriculation Examination in chemistry is one of the main sources for information on misconceptions of students. The analyses of the Matriculation Examinations in chemistry, over a period of more than 12 years, revealed each year that students have a fundamental misunderstanding and difficulties regarding these concepts. No doubt, the teaching and learning of these concepts is a serious and continuous problem. In this study we present several factors leading to these misconceptions. More specifically, we focus on how the structure and content of the National Matriculation Examinations conducted in Israel influence chemistry teaching and learning. We think that this type of assessment can be a major factor in the development of students' learning difficulties and alternative conceptions. [*Chem. Educ. Res. Pract.*: 2004, *5*, 301-325]

KEY WORDS: *chemical structure, chemical bonds, misconceptions, learning impediments, misleading factors, models, declarative knowledge, generative knowledge, scientific explanations and assessment tool.*

INTRODUCTION

"Many students say that chemistry is difficult. These perceived difficulties are part of the context in which these students develop chemical concepts and problem-solving skills"

(Carter &. Brickhouse, 1989, p. 223).

Chemistry, as a subject, is concerned with the properties and reactions of substances. Substances are often understood in terms of aggregations of particles, and the nature of the *bonding* between those particles is used to explain many of the chemical and the physical properties of the substance including such aspects as whether the substance is a solid, liquid or gas at a given temperature and pressure.

The theoretical content of chemistry is best seen as a set of models. Gilbert (1998) claims that models play a major role in all science disciplines; nevertheless, they seem to be particularly problematical to chemistry students.

Students live and operate in the macroscopic world of matter. Unfortunately, they do not perceive chemistry as related to their surroundings. Moreover, they do not easily follow shifts between the macroscopic and microscopic levels (Johnstone, 1991; Gabel, 1996; Tsaparlis, 1997; Robinson, 2003). Chemical concepts are very abstract and students find it difficult to explain chemical phenomena by using these concepts. The study of students' alternative conceptions and conceptual frameworks has been an active field among science educators for more than two decades. According to Gabel (1996):

> *"The complexity of chemistry has implications for the teaching of chemistry today. We know that chemistry is a very complex subject from both the research on problem solving and misconceptions …and from our own experience…Students possess these misconceptions not only because chemistry is complex, but also because of the way the concepts are taught"* (p. 43).

This study focuses on several aspects that have influenced students' misconceptions regarding the topic of *chemical structure and bonding*. In Israel, although there has been a serious effort to overcome this problem, the same misconceptions arise each year. We assume that most of these difficulties derive from the characteristics of chemistry learning, such as the central role of models, the linguistic cues, and phenomena explained through the sub-microscopic level.

Nevertheless, we have assumed that there are also external misleading factors, namely, the way the teachers teach (pedagogy, contents, and textbooks) and the way students learn, which lead to students' misconceptions.

In this study, we reviewed the analyses of the results of 12 years of chemistry Matriculation Examinations (Hofstein, 1991-1994; Bar-Dov, 1995-2003) regarding this topic. Based on these results, we investigated the sources for these misconceptions through further research with students, teachers, and scientists.

Our assumption was that one of the main factors, which is central to this problem, is the way students are evaluated. In this study we indicate that teaching and learning of this particular topic are very much influenced by the obligatory Matriculation Examination. Moreover, we suggest that these examinations, in their present form, in fact amplify students' misconceptions.

LITERATURE BACKGROUND

A review of the literature relates to *the chemical structure and bonding* conceptualization in several aspects. Students' misconceptions regarding this topic have been noted worldwide, and the following review presents the intrinsic characteristics of these central concepts, including several pedagogical components, which are associated with generating this problem.

The role of models

Chemistry as a discipline is dominated by the use of models. The range and sophistication of the scientific models used by chemists to understand *chemical bonding* is one factor that contributes to students finding this topic difficult (Gilbert, 1998). Students are poorer at modelling than teachers expect, and younger secondary school students usually do not look further than a model's surface similarities. They think that models are toys or small incomplete copies of actual objects, and therefore they do not look for ideas or seek purposes in the model's form (Harrison & Treagust, 1998). From the results of their studies, Justi and Gilbert (2002) strongly recommend that students should learn about the nature of models and their use as thinking tools and learn about the scope and limitations of specific chemical models. Teachers should encourage the use of multiple models for a given phenomenon.

Interestingly, teachers themselves may have misconceptions regarding scientific concepts and models. Some teachers conceive scientific models in mechanical terms and believe that models are true pictures of non-observable phenomena and ideas (Gilbert, 1991). Models are not "right answers"; they are scientists' and teachers' attempts to represent difficult and abstract phenomena in everyday terms for the benefit of their students. Chemistry teachers seem to focus their practice on the content of specific models, rather than on the nature of models and modelling (Van Driel, 1998).

In order to teach chemistry in the way that we have advocated, teachers need to have a clear and comprehensive view of the nature of a model in general, how their students construct their own mental models, how the expressed models can be constructively used in class, how to introduce scientific consensus models in their classes, and how to develop good teaching models and to conduct modelling activities effectively in their classes (Gilbert, 1997).

It is very important that students realize that no model is entirely correct and that they understand that science is more about thinking than just describing objects (Harrison & Treagust, 1998). Justi and Gilbert (2002) proposed that by using models, students' understanding of chemistry and models might be improved, as well as their ability to produce their own chemical models.

Regarding their mental models, teachers do not discuss them with their students, nor do they refer to their problems. According to Justi and Gilbert (2002), teachers do not emphasize neither the need for considering the scope and limitations of models during the process of modelling, nor the importance of discussing with the students such matters when presenting a model. They also claim that teachers must be the agents of such a revolution.

Harrison and Treagust (2000) claim that models are more than communicative tools: they are important links in the methods and products of science. Moreover, they suggest that students who participated in negotiating the shared and unshared attributes of common analogical models for atoms, molecules, and chemical bonds, actually used these models more consistently. In chemistry almost all models are metaphorical models.

Bhushan and Rosenfeld (1995) asked themselves: What happens when chemistry students fail to recognize the metaphorical status of certain models and interpret them literally? In what way might it detract from the goal we set ourselves as teachers, of facilitating the incremental expansion of our students' conceptual framework? They claim that metaphors may hinder insight into a problem, by blocking productive resolution of the problem. In their paper they analyzed three cases and detailed some cases in which metaphors can mislead rather than enlighten.

The metaphor is perhaps the most important part of the model for students. Thus, their recognition of a metaphorical status is crucial for avoiding misconceptions. In our discussions with students, we should ask them what they think the model shows them about this phenomenon.

The relations between internal and external representations

Chemical structure and bonding is a topic in which understanding is developed through diverse models, which, in turn, are built upon a range of physical principles; students are expected to interpret a disparate range of symbolic representations standing for chemical bonds (Taber & Coll, 2002). According to Johnstone (1991), matter can be represented on three levels, as represented in Figure 1. Frequently these are referred to as the macroscopic

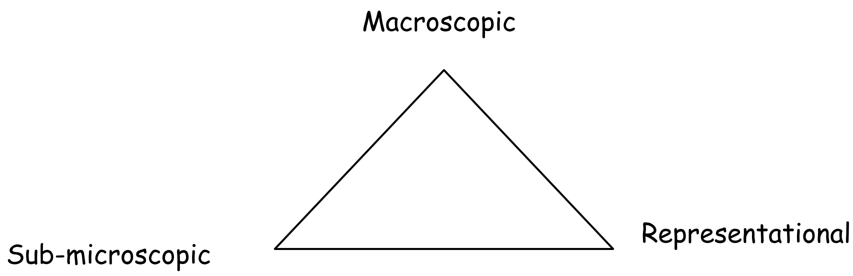

FIGURE 1: *Conceptual understanding of chemistry: A model for learning*

(physical phenomena), microscopic (particles), and the symbolic levels (chemical language and mathematical models).

Gabel (1996) claimed that often teachers unwittingly move from one level to another in their teaching. In that way, they do not help students integrate the levels, and each level can be interpreted in more than one way. Thus students become confused rather easily. More recently, Robinson (2003) has suggested that students must first thoroughly understand how to convert a symbol into the meaningful information it represents. Only then will they be able to cope with the quantitative computation.

According to Bodner and Domin (1998), it is very important to distinguish between internal representation, which is the information stored in the brain, and external representation, which is the physical manifestation of this information. Individuals with very different internal representations might write similar external representations. The instructor writes *symbols*, which represent a physical reality. Very often, students write *letters, numbers,* and *lines,* which have no physical meaning to them.

In order to understand the structure of matter, the students need to be familiar with the multiplicity of terms, with the meaning of scientific models, as well as the difference between the macroscopic and the sub-microscopic worlds.

Concepts and alternative conceptions

For the present, much has been said to indicate that learning specific concepts is very much at the heart of learning chemistry. Concepts like bonding, structure, rate of reaction, and internal energy apply to all chemical systems (Fensham, 1975). The comprehension of these concepts has implications regarding understanding the whole chemical process, mainly chemical reactions and chemical properties of substances. Chemical reactions involve the breaking and forming of chemical bonds (Taber & Coll, 2002). Therefore, *chemical bonding* is a key concept in chemistry.

As human beings grow and learn to cope with the process of living in the world, they make use of more and more generalizations. A concept, as it is used in education, means a generalization of one sort or another. It is used for several levels of generalization, but all its uses share this characteristic. Without concepts we could not begin to learn chemistry. But conceptualizing is a process of filtering reality, and we need to remember this, at all stages of learning chemistry (Fensham, 1975).

Students tend to build themselves alternative conceptions and mental models. Taber (2001a) believes that most alternative conceptions in chemistry do not derive from the learner's unschooled experience of the world. In chemistry, as opposed to biology or physics, the frameworks available for making sense of such abstract notions as molecular geometry or lattice structure derive only from the learners' understanding of prior science teaching. So how are they derived?

Students' alternative conceptions, which are considered to largely stem from the way they have been taught, have been labeled as pedagogic learning impediments (Taber, 2001b). The failure to represent the reactant molecules or lattice structures concerned is a simplification, which encourages students to develop alternative conceptions (Taber & Coll, 2002).

In the literature, there are many examples of students' misconceptions in chemistry, such as the belief that atoms in a metal are hard, but those in liquids are soft (Harrison & Treagust, 1996). According to Ben-Zvi, Eylon, and Silberstein (1986), many students do not distinguish between the properties of a substance and the properties assigned to a single, isolated atom. Students believe that the "particles" of a substance, called atoms or molecules, are very small portions of the 'continuous' substance. Any misconceptions and alternative conceptions that students harbor about the fundamental concepts of atoms and molecules will impede further learning (Griffiths & Preston, 1992).

The chemical bond: Pedagogy, conceptualization and misconceptions

As mentioned in the introductory part, we have assumed that there are several external factors that can generate students' misconceptions. If so, we have to ask ourselves how often are such misconceptions generated by the contents of textbooks and by teachers? How can teaching strategies and the way these concepts are presented in textbooks mislead students?

A review of the research relating to students' misconceptions of science concepts revealed that these misconceptions have common features. Students are often strongly resistant to traditional teaching and form coherent, though mistaken, conceptual structures (Driver & Easly, 1978).

The literature indicates several external factors that might cause learning impediments regarding the concepts of chemical bonds. Stinner (1995) and Sutton (1996) for example, claim that the analysis of current textbooks is of a pivotal importance because they constitute the most widely and frequently used teaching aids at all educational levels. Some analyses of science textbooks have shown that they tend to present science as a collection of true or complete facts and as generalizations and mathematical formulations, as if the material had been 'read directly from nature'. Curriculum developers, and therefore teachers, use as many accurate and precise definitions as possible.

In many chemistry textbooks, elements are conveniently classified as metals or non-metals (with a few semi-metals perhaps mentioned). In many cases this dichotomy among elements leads to a dichotomous classification of bonding in compounds: *covalent* being between non-metallic elements and *ionic* being between a metal and a non-metal.

In her research, Yifrach (1999) presents a scientist's view, claiming that the way textbooks and teachers present the classification of the chemical bonds, as if everything is very simple and clear (hydrogen bond, covalent bond, etc.) is deluding and misleading. This is not the nature of science. According to the scientist's view, one of the most important skills is the ability to classify intelligently. Thus, he suggests teaching students to classify originally by themselves in order to expand their understanding and to give them the opportunity to perceive the concepts from different points of view. In this way, the students can sharpen their thinking abilities and understand the relations between contents, skills, and the scientific process.

An intensive research study on students' misconceptions and learning impediments has been conducted by Taber (1995b, 1998, 2000, 2001a, 2002), mostly regarding the chemical bond concepts. Taber (1995b) suggests that in further learning, both dichotomies give way to continua. The elements may be categorized on an electro negativity scale, and bonding may be polar, although most compounds may still be considered to exhibit bonding of a type similar to the ionic or covalent model. In these terms, essentially covalent compounds will exhibit some degree of ionic character when there is a difference in electro-negativity between the elements. Ions may be polarized so that essentially ionic compounds can show some degree of covalent character.

Taber and Coll (2002) suggest that bonding may be an intermediate state between covalent and ionic. From a scientific point of view, most materials have bonding that cannot be considered as "purely" covalent or ionic (or metallic). In most materials, the bonding may be more precisely described as intermediate, with varying degrees of covalent and ionic (and metallic) character. The notion of bond polarity indicates that the covalent-ionic dimension should be seen as a continuum, and not as a dichotomy. Gillespie (1997) claims that:

> *"Electrostatic forces are the only important forces in chemistry"* (p. 862).

Taber and Coll (2002) argue that although electrical forces cannot be used to explain all aspects of chemical bonding, they do provide a comprehensive basis for starting to understand bonding phenomena. Thus, an authentic teaching model that is to be used to introduce chemical bonding, at an optimum level of simplification, should be based on the effect of electrical forces.

Gilbert (1998) suggests that many of the ideas used to understand chemical bonds are not accessible at an introductory level. Instead, curricula models need to be used in order to simplify the topic. Ideally, students will develop their own "tool kit" of bonding concepts as part of their progression in learning about the subject (Taber, 1995a).

Taber (2002) considers, as an example, the term *covalent bond* and suggests that most students entering secondary school do not know what it means. As they progress through school, encountering introductory and more advanced college chemistry, they construct a meaning as they learn the term in a range of contexts. According to Taber (2002):

> "*A young student who has just learnt the term of a covalent bond in a very limited context does not share the same set of meanings for the term as teachers. This is not a case of the teacher being right and the student wrong, but of them having a different concept of covalent bond. The teacher and the student use the same word, but…the teacher's meaning is not only extended, it is more sophisticated, more subtle, and more deeply integrated into a framework of chemical ideas"* (p. 56).

Finally, students do not possess the rich meaning of the term, as teachers do.

It is suggested that there is a gap between students and their teachers concerning students' understanding of these concepts, as well as in relating the task that they have to deal with. For the teacher the task is a routine exercise, but for the students it is a novel problem. The difference between an exercise and a problem is the result of differences in the level of familiarity with similar tasks that the individual brings to a given task (Bodner & Domin, 1998).

According to Robinson (2003), teachers often provide algorithmic formulas for solving problems rather than requiring students to use reasoning combined with an understanding of the concepts. Carter and Brickhouse (1989) state:

> *"What is particularly interesting are responses in which there is a large discrepancy between faculty members' view of the difficulties of general chemistry and that of their students. It appears that the two groups, at times, live in two different worlds"* (p. 224).

According to Erduran (2003), a lack of effective communication between students and teachers can lead to a mismatch between what is taught and what is learned. In the context of science lessons, symmetry between the nature of teachers' understanding of a particular science topic and students' ideas regarding this topic is critical, because such a match illustrates what scientific knowledge is being taught and learned in the classroom.

One way that teachers and textbooks simplify the physical and chemical concept is by using anthropomorphic explanations. For example, in his research, Taber (1998) showed that 10^{th} grades students commonly adopt as an explanatory principle the notion that atoms "want" to have "octets" or "full outer shells", and that chemical processes often occur to allow atoms to achieve this. Even some school textbooks incorrectly refer to eight electrons in the third or higher shells as a full shell.

The term "sharing", used to describe the covalent bond, often keeps its "social" connotations when used by students. For example, the shared electrons may be seen to still "belong" to specific atoms, and so bond fission is often assumed to be hemolytic, since each atom would "want" to get "its own" electron back. It could be argued that the uncritical and unthinking use of terms like "sharing electrons" by teachers and its use in textbooks is not helpful to students.

Taber and Coll (2002) suggest not learning by the "octet framework", which may lead to learning impediments. The existence of bonding, which does not lead to atoms having full electron shells, is consequently something of a mystery to many students. Moreover, students may have difficulty accepting anything that is not clearly explicable in "octet" terms as being a chemical bond. Hence, hydrogen bonding and van-der-Waals forces cannot be readily fitted into such a scheme, and the difference between inter-molecular and intra-molecular bonding is not clear to students.

According to Ben-Zvi & Mamlok (2000), if we wish to evaluate science curricula we must ask ourselves: Do science students gain a wide conceptual understanding of scientific concepts? And what models do students develop in order to explain natural phenomena? Justi and Gilbert (2002) claim that studies show that the curriculum developers always fail in making a contribution to students' understanding of the meaning of 'model'.

In summarizing the existing literature, we refer to Justi and Gilbert (2002), who claim that there have been only limited initiatives to promote the development of teachers' Pedagogical Content Knowledge (PCK) in this area. Shulman (1986) described PCK as

> "The most useful forms of content representation…, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that makes it comprehensible for others" (p.9).

The outcome of the current research may, hopefully, lead to interesting proposals for curriculum development.

RATIONALE FOR THE STUDY

This study is an attempt to identify the external factors that might mislead students in understanding the key concepts in this central topic. More specifically, the purpose of the study was to gain a better understanding of the influence of the Matriculation Examinations on the pedagogy and content by which these concepts are taught and learned.

Table 1 presents the *bonding and structure* concepts that are essential for understanding many other topics in chemistry, and which are part of the syllabus in many countries including Israel. In this study our goal was to reveal the linkage between students'

TABLE 1: *The essential role of the bonding and structure concepts for understanding many topics in chemistry.*

Topic	Core concepts of the subject	Bonding and structure concepts which explain these concepts
Carbon compounds	The state of matter Chemical reactions The compound properties: Boiling temperature Melting temperature Isomers	The structure of molecules Covalent bonds Inter-molecular bonds
Acids & bases	Defining Acids Defining Bases Chemical reactions Titration reaction	Hydrogen bonds Inter-molecular bonds The strength of bonds Electro-negativity
Energy	Chemical reactions (endothermic/exothermic) Enthalpy of formation Enthalpy of atomization Enthalpy of combustion	Inter-molecular & intra-molecular bonds Ionic bonds, metallic bonds Strength of bonds
Thermodynamics	Enthalpy Entropy Free energy	Inter-molecular & intra-molecular bonds Ionic bonds, metallic bonds The strength of bonds
Proteins	Chain formation The properties of proteins The structure & function of proteins Conformations	Intermolecular & Intra-molecular bonds Hydrogen bonds Molecules' structure Polar bonds Isomers
Carbohydrates	The properties of carbohydrates Structure & function Conformations	Inter-molecular & intra-molecular bonds Hydrogen bonds The structure of carbohydrates Isomers
Polymers	Chain formation The properties of polymers Melting temperature Glass transition temperature	Inter-molecular & intra-molecular bonds Hydrogen bonds The structure of molecules Isomers

misconceptions and the way they are evaluated in order to be able to solve the problem systemically.

The role of the Matriculation Examinations as an assessment tool, in chemistry teaching

In Israel, the National Matriculation Examinations in chemistry are one of the key sources for science teaching research regarding the misconceptions of students. Ben-Zvi and Hofstein (1996) suggest using the results and analyses of chemistry Matriculation Examinations as important sources of information for curricular change in Israel. The academic upper secondary school in Israel consists of three years of studies (the age range is 15-18 years). Chemistry is a compulsory subject in the first year (grade 10) and taking advanced courses is optional in the 11th and 12th grades. Those who opt for advanced courses in chemistry can be examined in the Matriculation Examinations, taken at the end of grade 12, at either the moderate (three credit points) or the high level (five credit points). In some high schools, students can be examined at the moderate level, which includes the topic *chemical structure and bonding,* at the end of grade 11.

For more than twenty years the Matriculation Examinations contain six or seven essay-type questions on specific topics with explicit titles. Each year, the examination includes one or two questions on the topic *chemical structure and bonding*. The questions are very similar each year. Moreover, the Matriculation Examination committees also prepare rubrics and fixed answers to be used by those who have to assess the examinations.

Dori (2003) claims that Matriculation Examinations in Israel have been the dominant summative assessment tool of high school students over few decades. A national committee appointed by the Ministry of Education is charged with composing the corresponding examinations and setting criteria for their grading. This leaves the teachers with little freedom to alter either the subject matter or learning objectives. Both pedagogical and socio-cultural aspects of the Matriculation system have been criticized. Pedagogically, this system forces teachers to emphasize teaching the subject in the way which will maximize their students' odds of success in the Matriculation.

According to Atzmon (1991) in Israel, throughout the years, a certain pattern of questions and a fixed-pattern structure for the Matriculation Examination in chemistry emerged. Indeed, the number of questions was changed in each chapter, also the ratio between multiple-choice questions and the conventional open ones; few units were dropped in favor of others, but despite all these measures, the general pattern was unchanged. A "dependable" teacher works with his students on solving Matriculation questionnaires for at least one-third of the lessons, because this is the permanent model of the coming exam. Single examinations, when viewed separately, might look challenging and point toward a demand for a high level of understanding, but in fact it is an easy test since the student was prepared ("trained") for it for a long time in rehearsing all the Matriculation questions from the last 15 years, by solving similar problems.

Concerning the standard examinations, Birenbaum (1997) argues that these examinations evaluate mainly declarative knowledge. Since the teaching itself is adapted to the level of the examinations, because of the highly related importance of their results, the level of the teaching itself is poor. We hear more and more claims from the public and professionals that the teaching emphasis is in preparing for these examinations; therefore, the fostering of high-level thinking, critical thinking, and articulation is neglected.

Analyzing the misconceptions of chemical structure and bonding: Findings in Israel

For a period of more than twelve years, Israel's National Matriculation Examinations in chemistry have been analyzed by a group of experienced teachers and researchers from The Department of Science Teaching, The Weizmann Institute of Science by a group of senior teachers. The Matriculation Examinations in chemistry are based on the high-school chemistry syllabus, which is prescribed by the Israeli Ministry of Education and designed by the Israeli Science Teacher Center (ISTC), which works closely with the Ministry of Education. In this study we have focused on the questions that are included in the Matriculation Examinations and are classified as *chemical structure and bonding* in order to investigate students' misconceptions regarding this topic.

Analyses of the Matriculation Examinations

This study is based on the analyses of questions from the chemistry Matriculation Examinations in Israel, over a period of more than 12 years. The main details of the analysis process are as follows:

The Matriculation Examinations are analyzed each year at the Weizmann Institute of Science by a group of 8-12 senior chemistry teachers (from now on called the *analyzers*). The teachers are selected strictly according to the following criteria:

a. Leading-teachers, who graduated from one of the leading courses (leadership courses).
b. Teachers who function as chemistry teachers' coordinators (heads of department of chemistry).
c. Teachers who have already evaluated chemistry Matriculation Examinations in the past, namely, assessed students' examination papers (in this paper they will be referred to as *senior evaluators*).

The senior evaluators estimate the distribution of the students' grades according to the sample results of the paragraphs and the sub-paragraphs of each question. The teachers who evaluate the examinations are asked to trace and document entire scope of students' quotations, which reveal the typical misconceptions.

Based on the distribution of the students' grades and other statistical results, the analyzers examine the collected data. The instructions they get regarding each open question are as follows:

- Task analysis (mainly: what the student has to know in order to answer the question).
- 2-3 quotations for each typical misconception.
- Proposed explanation regarding the sources of each typical misconception.
- Suggestions for pedagogical strategies, which may reinforce students' understanding in the specific relevant subject (such as: presentations, graphs, concepts maps, models, experiments, new questions and others).

Each year all these data and analyses are gathered together into one document.

In their research, Glazer (1998) and Glazer, Ben-Zvi, and Hofstein (1999) used the analyses of the Matriculation Examinations (1991-1996) as an assessment tool, in order to evaluate students' understanding of *chemical bonding* as well as their difficulties regarding scientific models. To this end, questionnaires were developed and interviews were conducted in order to learn about 11th grade students' perceptions of chemical bonding. These studies revealed crucial misunderstanding of scientific models.

The curriculum developers and chemistry teachers examined the analyses and the findings in order to increase their awareness of students' misconceptions. As mentioned before, we found, that despite the fact that teachers participate in professional development initiatives in which they learn how to teach these concepts, each year, the analysis of the Matriculation Examination questions has revealed crucial learning difficulties and misconceptions that students have regarding these key concepts.

More recent analyses, from the past six years (1997-2003), continue to indicate the existence of the same widespread misconceptions in this topic. The dilemma is the fact that the same misconceptions repeat themselves each year, and sometimes they even get worse.

The Israeli Ministry of Education reports that the average grades of the questions on this topic is about 75, each year, over the past twelve years. On the one hand, it is not such a low grade, but on the other hand, it is not getting better in spite of the enormous efforts to overcome the problem. Moreover, the fact that the average grade is not low does not necessarily indicate that the students understand the concepts.

According to Lythcott (1990), although it is assumed that problem solving is the application of understood knowledge, namely, students understand the chemistry then learn to solve problems, the results from her study indicate that this can clearly be a false assumption. Students can produce right answers to chemistry problems without really understanding much of the chemistry involved. Lythcott (1990) suggests that:

> "*This is a most unsettling piece of information. If, for example, correct problem solutions yield grades, but no guarantee that the chemistry has been understood, then one must seriously question what is being evaluated"* (p. 248).

We also have to ask ourselves, as educators, if we know how to teach in trying to achieve such an understanding. Did the students acquire any generative or meaningful knowledge? Perkins (1995) argues that students' knowledge is generally quite fragile in several different ways. He presents four problems with knowledge: missing knowledge, inert knowledge, naive knowledge and ritual knowledge, which he terms "the fragile knowledge syndrome". According to Perkins (1995):

> *"With the knowledge-telling strategy as their mainstay, students generally do not organize their knowledge into thoughtful theses and arguments"* (p. 29).

In this study we present evidence that in this topic students demonstrate mainly declarative knowledge and we assume that they learn these concepts and understand them poorly due to several misleading factors.

The accumulative information, which was collected and analyzed over the past twelve years, can be divided according to eight categories, as presented in Table 2. The categories are accompanied by students' quotations from the Matriculation Examination answers. The year of the Matriculation Examination is noted in parentheses.

These categories were validated by six members of the chemistry group in the Science Teaching Department at the Weizmann Institute of Science, along with a senior chemistry teacher, and are supported by Glazer, Ben-Zvi, and Hofstein (1999). After reviewing 12 years of Matriculation Examinations, we found that the most frequent problems were regarding their understanding of the nature of *chemical bonds* and the inter-molecular and intra-molecular bonding.

According to Taber (2000), students' explanations have largely been considered as data collected as evidence of students' conceptualizations of science topics. His research discusses the difference between a student's response to a question, a student's alternative conceptions, and a student's explanation. Students often use descriptions and over-generalizations instead of explanations in order to rationalize phenomena.

In the last Matriculation Examination (in 2003), according to the analysis, the average grade for *the chemical structure and bonding* question was the lowest one ever. In one of the paragraphs, the students scored an average grade of 52 points. They were asked to *explain* why HF has a higher boiling point than NH_3. Many students argued that ammonium is not a polar molecule. Others suggested that because of the high electro-negativity of the fluorine, there are many more hydrogen bonds in that compound than in the ammonium compound. Why do they get it wrong?

TABLE 2: *The categories of students' misconceptions in the topic:" chemical structure and bonding", accompanied by examples of students' quotations from the Matriculation. Examinations' answers.*

Examples	Categories
"CO_2 is a gas because it is a molecular compound"(2002). "Polar compounds dissolve in polar compounds" (1998). "If the molecule is bigger - the boiling temperature is higher"(2003). "It's an ionic compound, that's why it conducts electricity only when it's liquid" (2003).	1. Students use slogans, declarations and over-generalizations
"A molecule with hydrogen bonds will be liquid" (2001). "Sodium chloride consists of two ions" (1999).	2. Students relate to a single molecule as if it is an accumulation of molecules and vise versa
"I_2 is solid because the covalent bonds between the atoms are very strong" (1996). "The boiling temperature of LiF is higher than the boiling temperature of HF because the ionic bonds are stronger than the covalent bonds" (2003).	3. Students confuse inter-molecular and intra-molecular bonding
"$CH_3CH_2CH_2F$ is a gaseous compound because it consists of fluorine, which is a gaseous element" (2001). "CH_4 does not conduct electricity because it consists of the two elements: $H_{2(g)}$ and $C_{(s)}$, both of which do not conduct electricity" (2003).	4. Students tend to ascribe compounds by their elements' properties
"The inter-molecular forces between the NaCl molecules are stronger than those between the KI molecules…." (1998). "MgO is a polar molecule, so the electrostatic forces between the molecules are stronger" (2001, 2003).	5. Students confuse ionic compounds and molecular compounds
"Van der waals forces do not dissolve in water…" (1998). "In aqueous solution RbCl is decomposed into its ions. Thus, there are free electrons so the solution conducts electricity" (1992).	6. Students have difficulties regarding the type of particles in an aqueous solution
"$CH_3CH_2CH_2NH_2$ is liquid because its hydrogen bonds let it dissolve in water. Thus, it is liquid at room temperature" (2001). "Liquid LiCl conducts electricity because the ions are mobile in the aqueous solution" (2003). "CH_4 does not conduct electricity in a liquid state because it does not have hydrogen bonds, so it does not dissolve in water. Thus, there are no mobile hydrated ions" (2003).	7. Students confuse the melting process and the solubility process
"An ionic compound with higher electro-negativity has a higher melting temperature" (1998). "The melting temperature of LiCl is higher than the melting temperature of NaCl because the ionization energy of Li is higher than that of Na" (1996). "HF has more electro-negativity than NH_3" (2003).	8. Students do not understand the concepts of electro-negativity, electron affinity, ionization energy and polarity, and often confuse them

METHODOLOGY

Research hypothesis

Our key hypothesis is that the problem previously discussed, namely, the phenomenon of the same misconceptions regarding the topic *chemical structure and bonding*, arising each year for more than a decade, is systemic and that there are several misleading factors in the content and pedagogy of high-school chemistry that might cause this problem. The assumption we examined and discussed in this study is that one of the factors is the existence of the Matriculation Examination in its current version i.e. teachers teach the way they do in order to prepare their students to succeed in the Matriculation Examination, and apparently, this way of teaching and learning leads to a shallow understanding.

Research goal

The main goal of this study was to conduct a preliminary study, based on the analyses of the Matriculation Examinations, in order to bridge between the way students are evaluated and the phenomenon of the same misconceptions arising each year for more than a decade, despite systematic efforts to overcome the problem.

Research population

The research population in this study consisted of the following:

- A 12th grade chemistry class, in an academic high school situated in the center of Israel. This class included twenty students who had already been examined in the Matriculation Examination at the moderate level (three credit points). This examination took place at the end of the 11th grade and as usual, consisted of a question on the topic *chemical structure and bonding.* These students were asked to complete an open-ended-type questionnaire. In addition, five students, who were chosen by their chemistry teacher based on their verbal abilities as well as their achievements (two high-achievers, two medium-level students, and one low-achiever), were individually interviewed by one of authors of this paper immediately after the completion of the questionnaire.
- Twenty-seven senior chemistry teachers with at least 10 years' experience who had attended a leadership workshop for chemistry teachers and had undergone intensive professional development at the National Center for Chemistry Teachers (located at the Weizmann Institute of Science). This course was conducted in the academic year 2002-2003. In order to interview these teachers, we used the *focus group* method (for more details about this method see the next section).
- A random sample of 30 high-school chemistry teachers. This sample was drawn from the total number of chemistry teachers in Israel (N=400) who had several years of experience in preparing their students for the Matriculation Examination. These teachers volunteered to participate actively in this study. They filled out a Likert-type questionnaire aimed at determining their perceptions regarding how the Matriculation Examination influenced their way of teaching chemistry.
- A scientist (Naaman, 2003) from the Chemical Physics Department at the Weizmann Institute of Science. Naaman's field of research focuses on the structure of matter as well as chemical bonding and molecular reactions. He is also actively involved in studies on teaching chemistry, as a consultant and as a member of various committees involved in chemistry teaching.
- A chemistry educator (Gilbert, 2003) from the Institute of Education at the University of Reading, UK, who is actively involved in research on areas of learning chemistry that are

highly relevant to this study. Among other topics, he is involved in researching the issues of students' alternative conceptions, models, and modelling.

Note, that in Israel, chemistry is taught and learned based on the same syllabus and curricular materials. The syllabus and the materials are centrally developed by the Ministry of Education. Thus, all the students study the same curriculum and teachers teach using the same books.

PROCEDURES AND METHODS

In order to attain the goal of this study, namely, to bridge between the way students are evaluated and the phenomenon of the same misconceptions arising each year, we developed questionnaires as well as specific methods for interviewing the students and teachers. The development of these research tools was highly based on the findings of the Matriculation Examinations, which were collected over the period of 12 years. We focused on a few specific but diverse questions, which were selected from several Matriculation Examinations regarding the respective students' alternative answers. These questionnaires aid the researchers in using students and teachers as diagnosticians. Students' and teachers' views on several students' alternative answers are important information that might help us to ascertain our assumption regarding the sources of the problem.

The research tools and methods

1. Open-ended type questionnaire. An open-ended type questionnaire for students and teachers was developed based on the common questions from the examinations and the alternative answers of the students. These questionnaires were administered as a pilot study to 27 senior chemistry teachers. The teachers were asked to refer to the answers and record their views about each answer. The questionnaires were followed by group interviews. In addition, these questionnaires were administered to 20 chemistry students. The students were asked to refer to the answers and record their views about each answer. The questionnaires were followed by interviews with five students.

2. Interviews with a group of senior teachers. In order to interact with the teachers and discuss their views of students' alternative answers, we conducted a group interview (N=27). The group interview serves as an essential qualitative data-gathering technique in which the interviewer directs the interaction. The type of group interviews that we used in our study is called a *focus group* (Fontana & Frey, 1998). Merton, Fiske, and Kendall (1956) coined the term *focus group* to apply to a situation in which the interviewer asks group members very specific questions about a topic after considerable research has already been completed. The interviewer (one of the researchers) presented alternative explanations of two teachers concerning certain students' misconceptions. During the interview the teachers were asked to choose the explanation with which they agreed the most, and to present their arguments. During the session teachers were given opportunities to express their feelings regarding the examination in general, and toward the issue of bonding and structure in particular. The atmosphere and the environment of collegiality that existed in these workshops provided the teachers with a lot of freedom to argue, express their views, and concerns, and make suggestions about teaching chemistry. Thus, we thought that a *focus group* is a situation that very much resembles an individualized interview. The teachers' quotations were then assembled in a protocol and categorized according to four aspects (students, teachers, textbook and curriculum developers, and the Matriculation Examination).

3. Semi-structured in-depth interviews for the students. In order to conduct a thorough investigation of students' views about their colleagues' alternative conceptions, a semi-structured interview was developed. In this study, five individual interviews were conducted, with five 12^{th} grade students: two high-achiever students, two medium-level students, and one low-achiever student. The students were interviewed immediately after they had completed the questionnaires. Each of them was interviewed for about 20 minutes. The semi-structured interview consists of several open-ended questions, which we prepared based on the common alternative conceptions of the students. Nevertheless, during each of the interviews, we referred to only two or three of the planned questions, in order to stimulate the student, whereas most of the questions were unplanned. Therefore, the interviews were essentially unstructured and progressed spontaneously according to the students' responses.

4. A Likert-type questionnaire. This questionnaiure (N=30) regarded the influence of the Matriculation Examinations on teachers' instruction. The questionnaire is scaled 1-5 in which 5 is "totally agree" and 1 is "totally disagree", referring to eight items (see Table 3; α-Cronbach reliability coefficient = 0.82).

5. An interview with Prof. R. Naaman. Prof. Naaman (personal communication, 2003), is a scientist from the Chemical Physics Department, at the Weizmann Institute of Science. During the interview Naaman made several suggestions regarding the teaching and learning of the *chemical bonding* concept.

6. An in-depth interview with Prof. John Gilbert. Prof. Gilbert (personal communication, 2003) is a scientist from the Institute of Education at the University of Reading, UK, who investigated students' alternative conceptions and developed methods for modelling. During the interview Gilbert commented on the questionnaires and on the questions from the Matriculation Examinations.

RESULTS AND DISCUSSION

This study focused on the role of the Matriculation Examination, and its influence on the content and pedagogy of the teaching and learning of this topic. Naaman (2003) commented on several aspects of chemistry teaching, specifically regarding chemical bonds, which may hinder students' understanding. He referred to principles and key concepts such as electrostatic forces, the electro-negativity, and the "octet rule" model, and mentioned that curriculum developers have to change the way concepts are learned in order to provide students with sufficient explanatory power to certain phenomena

The way that this topic is taught is highly based on the definitions of the key concepts. Based on the syllabus and the textbooks, and according to the Matriculation Examinations demands, teachers tend to define these concepts in certain ways and to use "rules" and classifications that are not in alignment with the scientific theoretical models. As we already mentioned, the curriculum might cause learning impediments. No doubt, this problem requires further research toward revising a curriculum regarding the topic *chemical structure and bonding.*

The analyses of the Matriculation Examinations clearly indicate that students' misconceptions in this topic are a continuous problem. Regarding the database of the Matriculation Examinations analyses, Gilbert (2003) claimed that:

"It is a great opportunity to have access to all the data, natural data… almost nobody else has this in the world, and not only data for one year but over a number of years. It seems to me that …one is about the curriculum and who sets it, how it sets and why it sets, which leads into the examination - what is examined? There is a whole area there. There is quite clearly a big area about teaching and learning, these perceptions.... It seems to me in reading this that really what you have got is a disagreement between the teachers' perception and (but maybe also the curriculum…) what the kids get".

The following discussion relates to the way teachers teach this topic, and the way students learn it. The research results are discussed regarding the link between the need to achieve high grades in the Matriculation Examination and students' misconceptions. In this paper, several excerpts and quotations from the teachers' and students' transcripts are presented. We believe that these are valid representations of the total information and data that were collected during this study.

Teachers: Findings from the teachers' questionnaires and interviews

The teachers' answers to the open questionnaires were categorized. The results indicate that usually the teachers' explanations are directly connected to the most common problems, as mentioned in Table 2:

- Students confuse (1) intra-molecular bonds and inter-molecular bonds and (2) van-der-Waals forces and hydrogen bonds.
- Students tend to over-generalize and use slogans and declarations instead of scientific explanations.
- Students often know how to define the concepts but do not understand their meaning or their relevance.

The results of the Likert-type questionnaires regarding the influence of the Matriculation Examinations on teachers' instruction are shown in Table 3.

TABLE 3: *The results of the questionnaire about the influence of the Matriculation Examination regarding the way teachers teach chemistry* (N=30).

To what extent does the existence of the Matriculation Examination have an influence on:	**Percentage of teachers who highly agreed with this item**
The instructional methods in my classroom	50%
The level of instruction in my classroom	70%
The contents of the instruction in my classroom	87%
The questions I raise during my lessons	37%
The questions I ask in my examinations	87%
The questions I ask for homework	54%
The number of enrichment lessons on different subjects	55%
The number of in-depth classroom discussions (lessons in which the teacher discusses broad scientific explanations, more than is required according to the syllabus) on different subjects	63%

The teachers' quotations from the group interviews were assembled into a protocol and categorized according to the following four aspects: (1) students, (2) teachers, (3) textbook and curriculum developers, and (4) the Matriculation Examination. It is clear from the data that teachers tend to relate critically to their way of teaching, but on the other hand, to justify their way of teaching in connection to preparing their students to succeed in the Matriculation Examinations.

During one of the group interviews we discussed the sources of the misconceptions. Excerpts from the transcripts follow:

Teacher 1: *"Teachers direct their teaching towards the success of their students in the Matriculation Examination. I'm talking mainly about the successful teachers. A teacher is considered as successful if his students score high grades in the Matriculation exam. Thus, teachers teach their students how to succeed in the exam... so they teach them declarations, the "acceptable answer", the "way" they should answer. They teach rules. They don't teach them to think".*

Teacher 2: *"I think that during the first lessons, the teacher doesn't teach this topic in a declarative manner, but after he repeats the subject again and again, he tends to put things into "drawers" (i.e. metaphor like 'pigeon-holes', used to describe the way in which students tend to store information; teachers tend to use it to ease students learning) and he makes the mistake of teaching rules: how to pass the exam. At the beginning he teaches profoundly because he wants his students to understand, but later on, he tends to teach by rules and slogans, and the students are fixated by these "drawers".*

Teacher 3: *"Students find it convenient to see things through a generalization, and it might well be that we, the teachers are to blame for this, from our natural intention to ease the students' effort. So we tend to classify things for them. It is very convenient to have these indicators that tell you where you should look for things, although in chemistry and in life in general, things tend to be much more complex".*

Teacher 4: *"Students use "drawers" with very little understanding, mostly because we teach according to the Matriculation… specifications ……and we pay the price of superficial teaching instead of thoroughness –the students are familiar with the name of the material but they don't really know much more than that".....*

In the Matriculation Examination the students are frequently required to answer questions like:

Potassium Iodide (KI) does not conduct electricity at a temperature of 50^{o}C, but at 850^{o}C it does. **<u>Explain</u>** these facts.

Gilbert (2003) related to the type of explanations that students are required to give in the Matriculation Examinations in Israel, and claims the following:

> *"Because looking at the different answers is so problematic, and really, in many cases it is a type of explanation that is expected, I mean…it is not quite clear what…each question has got: "explain these facts"... What does "explain" mean?"…*

The Matriculation Examinations in Israel consists of questions that do not necessarily test profound understanding. Gilbert (2003) argues that:

> *"The* (word) ***"explain"*** *is too bold… so what you've got is children locking onto a different meaning of "explain". These are nice remarks made by the teachers (*in the

protocol of the group interviews*), and I think that one of them is quite right; it talks about students having fixations. I think what it means is that the children are being taught the material in a very* ***narrow context****:* ***one*** *situation,* ***one*** *example…. and they can't shift, and if you shift the context, you don't talk about Potassium Iodide, you talk about… Sodium Fluoride…they will be completely lost!!! You know? They get fixations on:* ***one*** *context,* ***one*** *compound. And you can't blame the students for this. It's the teachers* ***failing*** *to deal with it in terms of ideas, in terms of models and (*teach them*) what happens, and showing the kids the whole range of phenomena… The teachers, for whatever reason, are taking too narrow a view …Now, what will be really interesting is:* ***why do they do this****?"*

Here are some more examples from the questionnaires and the interviews:

Question 1: CO_2 is a gas at room temperature, whereas SiO_2 is solid at room temperature, with a very high melting point. Explain these facts.

Answer 1: One of the students claimed that: *"CO_2 is gas because it is a molecular compound".*
16 out of 21 teachers gave the following explanation:
The student over-generalized that if the melting point and the boiling point of molecular compounds are relatively low, and the forces between the molecules are weak, the compound must exist as a gas. The student has a fixation on a certain schema; he generalizes instead of explaining the facts.
Answer 2: Another student explained that: *"The bonds in CO_2, between the carbon and the two oxygen atoms, are weak (van der Waals bonds)".*

17 out of 21 teachers suggested the following: The student does not understand the differences between intra-molecular forces and inter-molecular forces.

Data shows (Bar-Dov, 1995-2003) that in many cases the mean score of the sub-paragraphs that relate to the intra-molecular forces and inter-molecular forces was lower than that of the entire questionnaire.

From the data shown in the next section, it appears that sometimes the teachers behaved intolerantly. The problem is that we, as teachers, tend to reduce the answers and limit the students' creativity. We tend to accept only our fixed version… and to reject every unexpected answer. For example, see the following:

Question 2: The boiling temperature of Cl_2O is higher than the boiling temperature of OF_2, but lower than the boiling temperature of H_2O_2. Explain these facts.

Answer 1: One of the students claimed that: *"The boiling temperature of H_2O_2 is high because it has more sites for polar bonds between the molecules".*

Most teachers, in referring to this answer, claimed in their questionnaires that the student was totally wrong. The frequent viewpoint was that the student did not mention the concept "hydrogen bonds". Gilbert (2003), in referring to these questionnaires, commented:

"You give them as you wrote the 'wrong' answer, but what happens is that many of the answers are reasonable in some way…"

Another example of teachers' intolerant behavior is exemplified in an interesting conversation between two teachers, which developed during their group interview. The dialogue is about a disagreement related to students' perceptions about electrical conductivity:

Sara: …"I also frequently use the method of correcting mistaken sentences".
Rami: …"What was the sentence that you asked them to correct"?
Sara: "They received the sentence: electrical conducting in ionic compounds is dependent on the existence of "free electrons". The students had to indicate whether it was correct or incorrect. If they suggested that it was incorrect, they had to correct it. However, I was surprised to find out that some of them answered that the sentence was correct".
Rami: "And why isn't it"?
Sara: "It is incorrect because in ionic compounds there are no free electrons".
Rami: "Yes, but why isn't it conducting? If there were free electrons it would have conducted"…
Sara: "Yes, that is correct".
Rami: "So – they believed that if there were free electrons the compound would conduct. And since there aren't any, it does not".
Sara: "Wait a minute; I'll try to reconstruct the sentence for you: "a solid ionic compound does not conduct electricity since there aren't free electrons".
Rami & Tami (the interviewer): "That is correct".
Sara: "Yes it is also correct"….
Rami: "It is true because if they were free electrons it would conduct".
Sara: …"so it would conduct…(with Rami) …(embarrassed and laughing)
..but if the sentence was: *An ionic solution conducts electricity because it contains free electrons*"???
Rami & Tami: "This is a different story"….
Sara: "O.K., this is a different story"….

From these interviews, it appears that the teachers hardly referred to the textbooks or to the curricular developers as potential sources of students' misconceptions. They often referred to the importance of preparing their students to succeed in the Matriculation Examinations.

The impact of the students' grades greatly influences the teachers' status and reputation. Thus, many teachers focus on preparing their students to answer the questions that refer to those instructions and rubrics. They adopt "instant teaching" by using rigid definitions (that are not necessarily scientifically correct), slogans, and formulas. We believe that these teaching strategies inhibit students from obtaining a good understanding of scientific concepts. Moreover, teachers tend to use incorrect generalizations, rubrics, and tables in order to facilitate teaching their students.

Some teachers react intolerantly to any answer not written in what they consider their adequate words. Lythcott (1990) refers to problem solving and suggests that:

> "*Perhaps it is the problems that are to blame. Some problems lend themselves to being solved by a set of procedures that can be memorized and applied in a rote fashion*" (p. 251).

In conclusion, all the above may lead to superficial teaching and poor learning, and may cause students' misconceptions.

Students

From the interviews conducted with the students and from the results of the questionnaires, we chose one student, Anat (false name). Anat is a medium-level achiever; she was interviewed right after the questionnaire was completed. She demonstrated self-confidence and motivation during the beginning of the interview. We present part of the transcript from her questionnaire and from the transcribed verbatim interview with her.

Parts from the questionnaire and the interview with Anat

The following data are presented in order to demonstrate the mismatch between students' declarations and their understanding of the actual meaning of the concepts. One of the questions in the questionnaire was as follows:

> The boiling temperature of Cl_2O is higher than the boiling temperature of OF_2, but lower than the boiling temperature of H_2O_2. Explain these facts.
> One of the students claimed that:
> "The intra-molecular bonds in the H_2O_2 molecule, which were created between the O atoms, are so strong that they cause it to have a higher boiling temperature".
> **Please write down your view regarding this answer.**

Anat explained that:

"The student didn't refer to the inter-molecular bonds, but rather to the intra-molecular bonds. This student didn't distinguish between inter-molecular bonds and intra-molecular bonds. In this question he should have referred to the inter-molecular bonds, the hydrogen bonds, and it is missing in his answer".

Part of the interview with Anat regarding her understanding of the concept of *hydrogen bonds* is as follows:

Tami (the interviewer researcher): "Students usually think that hydrogen bonds are covalent bonds between the hydrogen atom and another atom. What to you think"?
Anat (the interviewee): "Covalent bonds? But covalent bonds are 'intra'!!".
Tami: That is correct.
Anat: "They simply don't distinguish between inter-molecular bonds and intra-molecular bonds. They put everything together, in a group of bonds".
Tami: "If you were asked to draw molecules of water in a drop of water,… how would you draw these molecules"?
Anat: "It's impossible. There are so many molecules"…
Tami: "Right. So please draw 3-4 molecules, in a liquid state".
Anat: "What do you mean? (and she begins drawing…): O is connected with H and with another H" (see Figure 2).

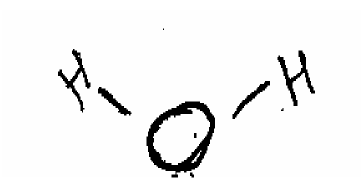

FIGURE 2: *Anat's drawing of a molecule of water.*

Tami: "That is correct. Now, try to draw another molecule; please show me where the hydrogen bond is".
Anat: (drawing another molecule and then drawing and showing the hydrogen bond, see Figure 3).

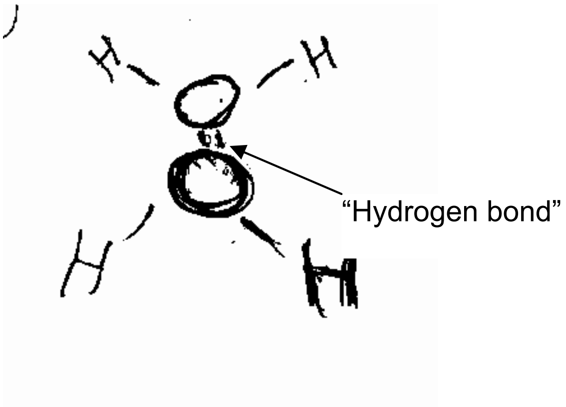

FIGURE 3: *Anat's drawing of two molecules of water, bonded by a "hydrogen bond".*

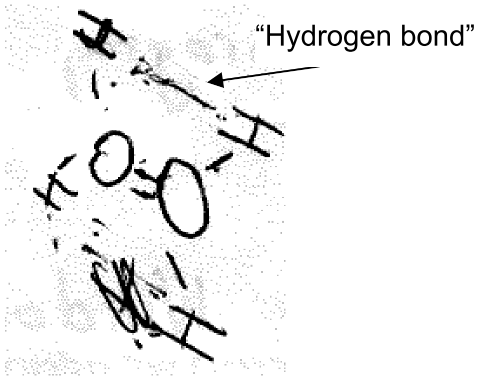

FIGURE 4: *Anat's drawing of two molecules of water, bonded by a "hydrogen bond".*

Tami: "The hydrogen bond is between two oxygen atoms"?
Anat: "No, it is in between. Namely, between all of this molecule and that entire molecule" (and she draws the bond between hydrogen and hydrogen, see Figure 4). "The bond is between H and H".
Tami: "The hydrogen bond is between the hydrogen and hydrogen"?
Anat: "Yes. It is between….no. Wait a minute (silence, trying to figure out from her drawing). "How was it? We learned it last year. Between H and H….no. Between O and O..…No?"
Tami: "Where is the bond derived from?"
Anat: "Between the elements NOF and H".
Tami: "Specifically, the NOF consists of nitrogen, oxygen, fluorine- and we have an oxygen atom, right? So in this case, the bond must be between oxygen and hydrogen. Students believe that the hydrogen bond is between oxygen and hydrogen in a molecule of water".
Anat: "No. We need at least two molecules of water".
Tami: "Right. So if you draw two molecule of water, then the hydrogen bond is between…"
Anat: "Between oxygen and oxygen. If I link them together?"
Tami: "Show me where the hydrogen bond is …you told me earlier that it is between…".
Anat: "Here (and she is points at the space between the two oxygen atoms, in Figure 4). "The bond is between the two molecules".
Tami: "You mean between the two oxygen atoms?"
Anat: "Yes".
Tami: "Why should they attract each other? Which charges do the oxygen atoms obtain? Did you learn about polar molecules?"
Anat: "The molecules are polar".
Tami: "So where is the negative pole of the water molecule? Did you learn about δ+ and δ-?"
Anat: "The spreading of the electrons is here (she points at the oxygen)."
Tami: "The oxygen is…."
Anat: "Electro-negative".
Tami: "Right. So the negative charge is on the oxygen. Right?"
Anat: "Yes".
Tami: .."And there is a negative charge on this oxygen too?"
Anat: "Yes".
Tami: "So why should a negative charge be attracted to another negative charge?"
Anat: "Because polarity has two characteristics: the spreading of the electrons and the electro-negativity, so, even though it is equal, there is spreading of the electrons".
Tami: "O.K. Previously you mentioned that NOF is attracted to hydrogen, and that this is the hydrogen bond. So what is the NOF?"

Anat: "The O".
Tami: "And it is supposed to connect to…."
Anat: "To the H".
Tami: "So the hydrogen bond is between what and what?"
Anat: "Between O and H."
Tami: "So can you please show the bond between the hydrogen and the oxygen".
Anat: "Between the hydrogen and the oxygen?"
Tami: "Yes. One hydrogen bond, can you please draw it with a striped line?"
Anat: "One hydrogen bond? I don't understand your question."
Tami: "Try to draw one hydrogen bond, where is it created?"
Anat: "Between the oxygen and the hydrogen" (and she points at the covalent bond in the molecule, see Figure 5).
Tami: "So the bond is in the molecule"?
Anat: "No".
Tami: "So where is it?"
Anat: "Here. With another hydrogen, it is clear that the bond is with a hydrogen in another molecule, because it is an inter-molecular bond and not an intra-molecular bond!"

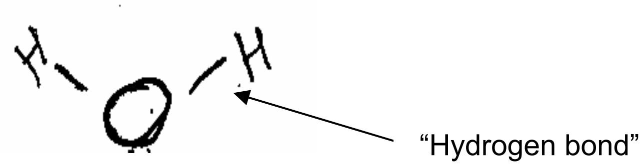

FIGURE 5: *Anat's drawing of a molecule of water.*

From the data presented above, it is clear that even when Anat's answers in the questionnaire and during the first questions of the interview were correct, and her "explanations" seemed to be correct, it does not mean that she really understands the meaning of the concept *hydrogen bond*. Her "explanations" about intermolecular bonds are indeed correct, but her answers in the interview indicate that her understanding of these concepts is shallow.

The teachers who participated in our research claim that students tend to learn and to memorize facts and obtain their knowledge according to slogans and rigid frameworks. They tend to know facts, rules, and formulas but have very little understanding of the actual meaning or the context of the phenomena. In addition, they tend to memorize the concepts' definitions, in the exact words that their teachers use, in order to succeed in the Matriculation Examination.

These results are supported by Shwartz (in preparation) who interviewed 12th grade chemistry students, in Israel, regarding their views of the chemical studies.
Two students, who graduated 12th grade, claimed the following:

Student 1: *"We and the teacher and had only one goal in mind: to finish this matriculation exam. We didn't study in order to understand chemistry.. We study because we have to pass the test at the end of the year"…*

Student 2: *"Chemistry studies in 10th grade are very different from those of 11th and 12th grade. In 10th grade you really want to know things, to understand, but in the last two years you just study things and remember them by heart for the Matriculation exam, with no understanding".*

CONCLUSIONS AND IMPLICATIONS

We may conclude that students possess these alternative conceptions not only because this topic has its intrinsic complexities. Students' misconceptions stem also from several misleading factors. We have mentioned the content and pedagogical components, but we assume that the way students are evaluated is critical to the way this topic is taught. More specifically, we claim that the existence of the Matriculation Examination in its current form causes students to use slogans and declarations, explain facts by "drawers", and students demonstrate a very shallow understanding of the key concepts. According to Atzmon (1991), Birenbaum (1997), and Dori (2003), this system of assessment detracts from teachers' efforts to ensure meaningful learning and the development of students' higher-level thinking abilities.

In light of this, we highly recommend abandoning the current pattern of fixative questioning and instead to form new assessment tools. Gilbert (2003) criticized the way of questioning, and claimed that the teachers' role is to change this system. He suggested using completely different teaching and assessment methods. We suggest not examining a narrow range of skills, but instead to evaluate students' argumentation and thinking skills as well as the skills in creativity. Such a change requires developing a new curriculum and promoting the development of teachers' PCK. Therefore, an improvement will occur only by a systemic solution such as revising the curriculum, the assessment method as well as the teaching methods.

CORRESPONDENCE: *Avi Hofstein, Department of Science Teaching, The Weizmann Institute of Science, Rehovot, 76100, Israel; fax: 972-8-9344115; e-mail: avi.hofstein@weizmann.ac.il*

REFERENCES

Atzmon, A. (1991). *Natural science curriculum as designer of the image of science using rhetorical patterns within the socio-political system*. Unpublished doctoral dissertation (in Hebrew), Hebrew University, Jerusalem.

Bar-Dov, Z. (1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003). *The analyses of the Matriculation Examination*. Manuscripts (in Hebrew), Weizmann Institute of Science, Rehovot.

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

Ben-Zvi, R. & Mamlok, R. (2000, April). *Is there a link between curriculum content and students' understanding of the concept of energy*? Paper presented at the annual meeting of the National Association for Research in Science Education, New Orleans, LA.

Ben-Zvi, R. & Hofstein, A. (1996). Strategies for re-mediating learning difficulties in chemistry. In F. Treagust, R. Duit, & B. Fraser (Eds.), *Improving teaching and learning in science and mathematics* (pp. 109-119). London: Teachers College Press.

Bodner, G. & Domin, D. (1998). Mental models: The role of representations in problem solving in chemistry. International Council for Association in Science Education, Summer Symposium, Proceedings.

Bhushan, N. & Rosenfeld, S. (1995). Metaphorical models in chemistry. *Journal of Chemical Education*, *72*, 578-582.

Birenboum, M. (1997). *Alternatives in assessment.* Tel-Aviv: Ramot.

Carter, S. & Brickhouse, N. (1989). What makes chemistry difficult? *Journal of Chemical Education*, *66,* 223-225.

Dori, Y.J. (2003). From nationwide standardized testing to school-based alternative embedded assessment in Israel: students' performance in the matriculation 2000 project. *Journal of Research in Science Teaching*, *40*, 34-52.

Driver, R. & Easly, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education*, *5*, 61-84.

Erduran, S. (2003). Examining the mismatch between pupil and teacher knowledge in acid-base chemistry. *School Science Review*, *84*(308), 81-87.

Fensham, P. (1975). Concept formation. In D. J. Daniels (ed.), *New movements in the study and teaching of chemistry,* pp. 199-217. London: Temple Smith.

Fontana, A. & Frey, J. (1998). Interviewing: The art of science. In N. Denzin, & Y. Lincoln (Eds.), *Collecting and interpreting qualitative materials* (pp. 47-78). Thousand Oaks, CA: SAGE.

Gabel, D. (1996, July). The complexity of chemistry: Research for teaching in the 21st century. Paper presented at the *14th International Conference on Chemical Education*. Brisbane, Australia.

Gilbert, J. (1991). Model building and a definition of science. *Journal of Research in Science Teaching*, *28*, 73-79.

Gilbert, J. (1997). Models in science and science education. In J. Gilbert (ed.), *Exploring models and modelling in science and technology education: Contributions from the MISTRE Group*, pp. 5-19. Reading: The University of Reading, Faculty of Education and Community Studies.

Gilbert, J. (1998). Explaining with models. In M. Ratcliffe (ed.), *ASE Guide to Secondary Science Education,* London: Stanley Thornes.

Gilbert, J. (2003). Personal communication.

Gillespie. R. (1997). The great ideas of chemistry. *Journal of Chemical Education*, *74*, 862-864.

Glazer., N. (1998). *Students' misconceptions and learning difficulties of the concept: "Chemical bonding and properties of substances"*. Unpublished master's thesis (in Hebrew). Weizmann Institute of Science, Rehovot.

Glazer. N., Ben-Zvi. R., & Hofstein. A. (1999, March). The gap between factual knowledge and conceptual understanding in learning the concept "chemical bonding", Paper presented at the annual meeting of the National Association for Research in Science Teaching, Boston, MA.

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

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

Harrison, A. G. & Treagust, D. F. (1998). Modelling in science lessons: Are there better ways to learn with models? *School Science and Mathematics*, *98*, 420-429.

Harrison, A. G. & Treagust, D. F. (2000). Learning about atoms, molecules, and chemical bonds: A case study of multiple-model use in grade 11 chemistry. *Science Education*, *84*, 352-381.

Hofstein, A. (1991, 1992, 1993, 1994). The analyses of the Matriculation Examination. Manuscripts (in Hebrew), Weizmann Institute of Science, Rehovot.

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

Justi, R. & Gilbert, J. (2002). Models and modelling in chemical education. In J. K. Gilbert, O. D. Jong, R. Justy, D. F., Treagust, & J. H. Van Driel (eds.), *Chemical education: Towards research-based practice,* pp. 47-68. Dordrecht: Kluwer.

Lythcott, J. (1990). Problem solving and requisite knowledge of chemistry. *Journal of Chemical Education*, *67*, 248-252.

Merton, R. K., Fiske, M., & Kendall, P. L. (1956). *The focused interview*. Glencoe, IL: Free Press.

Naaman, R. (2003). Personal communication.

Perkins, D. (1995). *Smart schools- Better thinking and learning for every child*. New York: The Free Press.

Robinson, W. (2003). Chemistry problem-solving: Symbol, macro, micro, and process aspects. *Journal of Chemical Education*, *80*, 978-982.

Stinner, A. (1995). Science textbooks: Their present role and future form. In S. M. Glynn & R. Duit (eds.), *Learning science in the schools,* pp. 275-296. Mahwah, NJ: Lawrence Erlbaum Associates.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4-14.

Sutton, C. (1996). Beliefs about science and beliefs about language. *International Journal of Science Education, 18*, 1-18.

Shwartz, Y. (in preparation). *Chemical literacy: Defining it with teachers and assessing its expression at the high-school level.* Doctoral dissertation (in English). Weizmann Institute of Science, Rehovot.

Taber, K. S. (1995a). An analogy for discussing progression in learning chemistry. *School Science Review*, *76*(276), 91-95.

Taber, K. S. (1995b). Development of student understanding: A case study of stability and lability in cognitive structure. *Research in Science & Technological Education*, *13*, 89-99.

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

Taber, K. S. & Watts, M. (2000). Learning explanations for chemical phenomena. *Chemistry Education: Research and Practice*, *1*, 329-353. [http://www.uoi.gr/cerp]

Taber, K. S. (2001a). Building the structural concepts of chemistry: Some considerations from educational research. *Chemical Education: Research and Practice*, *2*, 123-158. [http://www.uoi.gr]

Taber, K. S. (2001b). The mismatch between assumed prior knowledge and the learners' conceptions: A typology of learning impediments. *Educational Studies*, *27* (2), 159-171.

Taber, K. S. (2002). *Chemical misconceptions – prevention, diagnosis and cure: Vol 1: Theoretical background*. London: Royal Society of Chemistry.

Taber, K. & Coll, R. (2002). Bonding. In J. K. Gilbert, O. D. Jong, R. Justy, D. F., Treagust, & J. H. Van Driel (eds.), *Chemical education: Towards research-based practice,* pp. 213-234. Dordrecht: Kluwer.

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

Van Driel, J. H. (1998, April). Teachers' knowledge about the nature of models and modelling in science. Paper presented at the annual meeting of the *National Association for Research in Science Education*, San Diego.

Yifrach, M. (1999). *Definition of chemical literacy and assessment of its attainment in high school chemistry*. Unpublished master's thesis (in Hebrew). Weizmann Institute of Science, Rehovot.