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RESEARCH REPORT

# A Macro–Micro–Symbolic Teaching to Promote Relational Understanding of Chemical Reactions

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The purpose of this research is threefold: (1) to identify the difficulties that Grade 10 students in a Lebanese school have that hinder their conceptual understanding at the micro–macro–symbolic interface in chemistry, (2) to investigate the effect of a macro–micro–symbolic teaching approach on students' relational understanding of chemical reactions, and (3) to characterize students' conceptual profiles regarding their understanding of chemical reactions in terms of macro, micro, symbolic levels and the relations among them, at the end of the teaching sequence. Forty six 10th graders from two sections participated in the study. A student-centered approach was followed in both sections based on constructivist pedagogy. Hence the teacher played the role of a facilitator who guided students in a meaning making inductive learning process, through questioning, monitoring, validating, and clarifying ideas. Instruction in the experimental group was characterized by macro–micro–symbolic teaching that focuses on the interplay between the levels, integrates various representations, and engages students in an epistemic discourse about the nature of knowing in chemistry. Data sources for the study included a pre-test and two post-intervention tasks: a post-test and a concept map task, in addition to interviews with selected students from both sections. Findings indicated that macro–micro–symbolic teaching enhanced students' conceptual understanding and relational learning of chemical reactions. Besides, four assertions related to students' conceptual and epistemological thinking in response to the different teaching approaches are presented. Implications for instruction and for teacher education programs, as well as recommendations for further research, are discussed in light of these findings.

Keywords: *Chemistry education; Chemical reactions; Epistemic discourse; Nature of chemistry; Macroscopic–microscopic–symbolic levels*

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For the last few decades, constructivism was and continues to be the leading paradigm in science education. In light of this framework, learning is viewed as the active process of meaning making in the mind of the learner, against a background of prior knowledge and experiences. During this process, teachers can have a pivotal role in helping students gradually integrate and reconstruct the conceptual structure of the academic discipline under study, such as chemistry. This is not to suggest that such an endeavor is simple, straightforward, and guaranteed to succeed. On the contrary, many challenges teachers and students face on their way toward knowledge construction; challenges that are peculiar to the various academic disciplines. Chemistry is particularly conceived by many as a difficult subject to teach and learn (see Johnstone, 1991; Nakhleh, 1992; Taber, 2002a). Accordingly, the purpose of this study is to explore some of the difficulties that students encounter in chemistry and to investigate the potential effect of a particular teaching intervention in reducing these difficulties.

Educational research in chemistry focused on two areas from which complexities arise, classifying these latter into two types: (1) epistemological impediments related to chemistry as a discipline, and (2) pedagogical learning impediments related to the nature of learning and information processing. Below we present the two types of impediments and review some central frameworks commonly used in the literature to conceptualize these impediments.



## Epistemological Impediments

By its nature, chemistry deals with a sub-microscopic world as well as with an observable or phenomenological world, both of which are communicated through the use of symbols. Johnstone (1982) proposed a model of thinking in chemistry that consists of three levels: the macro, the micro, and the symbolic. This multi-leveled way of thinking can be represented by the corners of a triangle, as illustrated in Figure 1, comprising (a) the macro and tangible including observable and sensory phenomena, (b) the micro (also known as sub-micro) including atoms, molecules, ions, etc., and (c) the symbolic or representational comprising formulas, equations, molarity, mathematical manipulation, and graphs (Johnstone, 2000). Integrating these levels and shifting among them represent important processes needed for a good understanding of chemistry (Johnstone, 2000); processes that by themselves necessitate a thinking demand that is challenging and hence might be considered an impediment to understanding chemistry, stemming from the very nature of chemistry as a discipline.

Moreover, 'chemistry as a discipline is dominated by the use of models' (Levy Nahum, Hofstein, Mamlok, & Bar, 2004, p. 302); this high reliance on models and on abstract, theoretical thinking requires students to have an appreciation of both the role of models and the nature of explanations and to operate at an abstract formal thinking level, in the Piagetian sense. As Levy Nahum et al. (2004) suggest, 'in chemistry, almost all models are metaphorical models' (p. 303). Therefore, the features and attributes of models should not be transferred directly but rather in

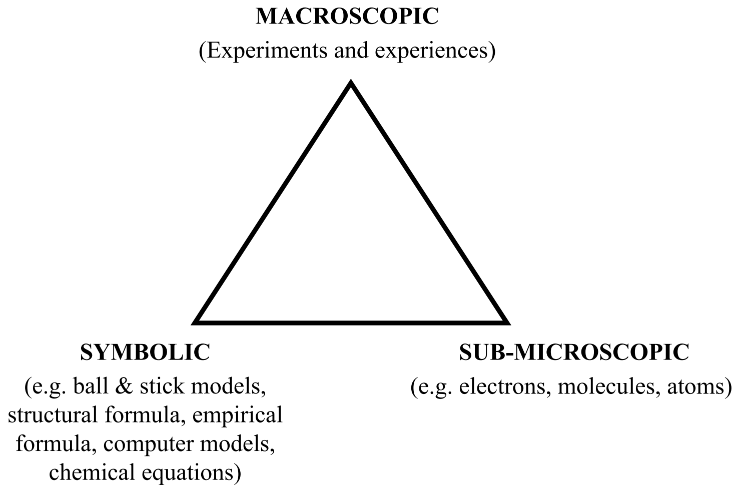



Figure 1. The three representational levels in chemistry (Johnstone, 1991)

analogical and symbolic ways. In other words, models should be used as tools to approximate rather than directly reproduce or mirror reality in ways that facilitate our explanation and prediction of chemical phenomena. Failing to do so might lead to the formation of alternative conceptions and represent a barrier to learning and appreciating chemistry. In fact, there were many calls in the chemical education literature to teach modeling skills and help chemistry learners to develop adequate epistemology of models (e.g. Bodner & Domin, 2000; Justi & Gilbert, 2002; Kozma & Russell, 1997). In their investigation of the role of mental models in problem solving in chemistry, including problems about chemical reactions, Bodner and Domin (2000) claimed that encouraging students to work with various representational and symbolic models helps them recognize the important key information needed to answer a problem. Justi and Gilbert (2002) added that in order to provide good chemistry teaching, teachers are strongly recommended to present students with opportunities to develop and test their produced models and to explicitly teach about the nature of models including their functions and limitations. These teaching practices will enable students to develop 'representational competence'; what Kozma and Russell (1997) referred to as core to the chemistry curriculum. The authors defined this competence as the ability to identify, analyze, and interpret features of one or many representations, the skill of transforming representations into other forms, and the ability to generate a representation and to explain its appropriateness. All of these skills highlight again the need for students to appreciate the epistemological nature of models and modeling and to learn and practice working with models. In sum, these epistemological challenges can become barriers to students' endeavor to build an interconnected chemical knowledge that integrates the three levels of chemical representations: the macro, the micro, and the symbolic levels.

## Pedagogical Learning Impediments

Treagust, Chittleborough, and Mamiala (2003) provide a framework for diagnosing the relationships between levels of understanding and levels of chemical representations that vary across a continuum from instrumental understanding (knowing how) to relational understanding (knowing why), as shown in Figure 2.

When learners develop relational understanding, they acquire ways to move easily and skillfully within the macro–micro–symbolic triangle, linking meaningfully the various chemical concepts. In order to do so, learners must be first aware of the existence of the three levels, and then should be trained to do the 'mental gymnastics' (Johnstone, 1991) to shift between them. On the other hand, learners who operate at the instrumental understanding mode, learn chemical concepts at the three levels, the macro, the micro, and the symbolic, separately, in a discrete manner, which leads to fragmented and compartmentalized knowledge (Treagust et al., 2003). In this situation, students might solve problems systematically and algorithmically, however, they might not be able to understand thoroughly the chemical meanings behind the problems, and might even develop inaccurate understandings of the chemical phenomena.

In light of the epistemological and pedagogical impediments associated with learning chemistry, this study is aimed at designing an instructional intervention that facilitates students' endeavor as they learn chemistry in order to foster relational conceptual understanding, when learning about chemical reactions.

## Purpose

As reviewed by Laugier and Dumon (2000), the history of chemistry reveals that the dilemma related to representing a chemical reaction at the microscopic level versus the macroscopic level constituted an epistemological obstacle to chemists until the

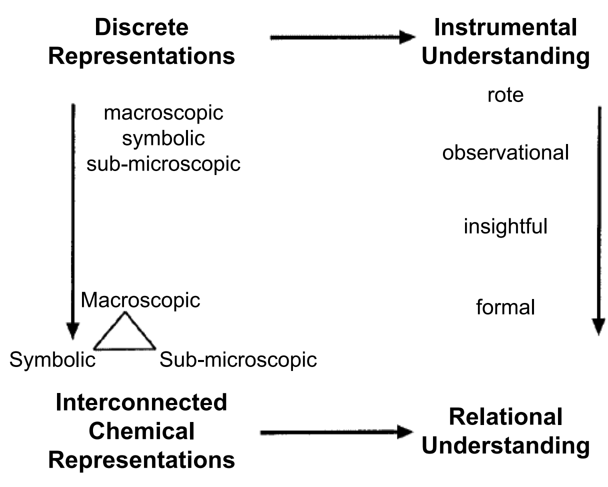



Figure 2. Relationship between levels of understanding and chemical representations (Treagust et al., 2003)

nineteenth century. Laugier and Dumon (2000) note that it was not until the work of Cannizaro (1860) and Mendeleev (1869) appeared that chemists could resolve this conflict by underscoring the need to operate both at the macro- and the micro-levels, and to shift between them, in order to understand transformation of matter. This epistemological challenge found its way into school chemistry (Tsaparlis, 2000) as documented by the voluminous number of studies identifying students' persisting challenges when dealing with chemical reactions. In fact, a synthesis of research (e.g. Anderson, 1990; Ben-Zvi, Silberstein, & Mamlok, 1990; Brosnan, 1990; Duit, 2006; Horton, 2001; Kind, 2004; Sequeira & Leite, 1990; Taber, 2002a) highlights that physical and chemical transformation of matter, alongside the particulate nature of matter, presents a particularly challenging topic at the macro–micro–symbolic interface for students in chemistry classes.

Moreover, it is evident that research focused mainly on exploring, describing, and outlining difficulties rather than addressing them. Surprisingly, very few studies investigated teaching interventions that were designed to target these difficulties (see Georgiadou & Tsaparlis, 2000; Russell et al., 1997). Thus, there is a need to pursue this line of research by investigating the effect of pedagogical strategies informed by findings and insights from previous research. Consequently, this study sets out to address Grade 10 students' difficulties that stem from the back and forth shifting between the three levels (macro, micro, and symbolic), characteristic of chemistry, when learning about chemical reactions. Specifically, the study aims at answering the following questions:

(1) What are the difficulties that Grade 10 students in Lebanon have that hinder their conceptual understanding in chemistry, regarding the micro–macro–symbolic interface?
(2) Does a student-centered pedagogical approach that (a) focuses on the interplay between the macro, the micro, and the symbolic levels, (b) integrates the use of various schematic representations (such as diagrams, pictures, graphs, drawings, and other symbolic illustrations), and (c) incorporates an epistemic discourse on the nature of chemical knowledge and modeling, improve students' relational understanding of chemical reactions as compared to other student-centered teaching approaches?
(3) What are the main characteristics of students' conceptual profiles regarding their understanding of chemical reactions in terms of macro, micro, symbolic levels and the relations among them, in response to the teaching approaches presented in question 2?

## Method

### *Context and Participants*

The study lends itself to a mixed methods research design, with both quantitative and qualitative aspects. Forty six students were selected to participate in the study from two Grade 10 sections in a Lebanese coeducational school with a long educational history, located in Beirut. These students were enrolled in the American Program where science is taught in English. The selected students represent the relatively diverse population of the school, coming from a variety of socioeconomic and religious classes. The two sections involved in the study were randomly assigned either to a control or experimental condition. The intervention lasted for around five weeks, with four hours of chemistry teaching per week. The chemistry content during this intervention was centered on chemical reactions and included characterizing features, types, and equations of reactions, conceptually defining and experimentally measuring rates of reactions, determining stoichiometric conditions, and making stoichiometric calculations. An experienced male chemistry teacher taught both sections. One of the researchers and the teacher met on a regular basis to discuss the implementation of the lessons, assess their flow, and the level of compliance with the experimental and control conditions. Moreover, in order to increase the internal validity of the design, the sessions were observed and videotaped by one of the researchers. After each session, the same researcher and the teacher met to discuss any emerging issues and ways to address them.

### *Instruments*

The instruments used in this study consisted of a pre-test, a post-test (Appendix), and a concept map task. The pre-test was partly used to assess the equivalence between the two groups prior to the inception of the study. Moreover, the pre-test served as a basis to detect students' difficulties regarding the macro–micro–symbolic interface. By verifying the initial prevalence of such difficulties, the pre-test provides a rationale for the suggested teaching intervention. This pre-test consists of some items developed by the researchers and others adapted from chemistry resources available in the literature (e.g. Mulford (Chemical Concepts Inventory), 1996; Paradis, 2007; Salloum, 2000; Taber, 2002b). The pre-test was designed specifically to target the three-leveled nature of chemistry and hence items were chosen to address these levels and the relationships among them. The test was discussed with and reviewed by the chemistry teacher. Moreover, three other experienced chemistry teachers reviewed the test to check for objectives and content validity. The pre-test was corrected and scored by one of the researchers and by the teacher separately, and any discrepancies were discussed until consensus was reached.

After the instructional intervention, students sat for a conceptual chemistry post-test that reveals students conceptual understanding regarding chemical reactions. The post-test items are directly related to the new content taught during the intervention period. Some test items were developed by one of the researchers and the teacher, and some items were adapted from chemistry resources available in the literature (e.g. Salloum, 2000; Taber, 2002b). Moreover, the post-test was designed specifically to target the three-leveled nature of chemistry and hence items were chosen to address these levels and the relationships among them. Again, this test was reviewed by three experienced chemistry teachers, the same teachers who reviewed the pre-test, to check for objectives and content validity.

Moreover, in order to explore the level of sophistication of their conceptual understanding, students were asked to construct concept maps to represent their knowledge about what happens in a number of chemical reactions. Students were in fact provided with two cases illustrating two chemical phenomena. Through focus questions, students were asked to list as many ideas as they can in each case in order to describe, explain, and symbolically represent the observed phenomenon, and then to present these ideas and the relations among them in a concept map. Students were given a model of a concept map that they could use as a guide to provide some sense of directedness and focus, following the framework provided by Ruiz-Primo and Shavelson (1996). For further triangulation, eight students were purposively selected, based on their concept map scores, for an interview to explain the reasoning behind their concept maps.

### *Pilot Study*

The conceptual chemistry pre-test, three lesson plans of the macro–micro–symbolic teaching intervention, and the post-test were pilot tested with a volunteer group of five International Baccalaureate students from the same school. Most questions were not problematic, however, concerns were raised regarding clarity of diagrams, the nature of some questions, and time needed for post-test. We addressed these concerns by modifying unclear diagrams and the wording of some questions and by providing extended time for the post-test.

### *Procedure*

On the first day of the research study, all students completed the conceptual chemistry pre-test described in the instruments section. During the study, a student-centered instructional approach to teach chemical reactions was followed in both sections in line with constructivist pedagogy. Hence the teacher played the role of a facilitator and a guide who engaged students in a meaning making inductive learning process during classroom discussions through questioning, monitoring, validating, and clarifying idea. However, the control and experimental groups experienced different kinds of lesson plans that were particularly designed for each section. On the one hand, the control group was subject to lesson plans and worksheets that target conceptual understanding, using a variety of examples of chemical reactions as well as quantitative problems, however, without explicit attention to the epistemological nature of chemistry. To account for the time provided for the epistemic focus of instruction in the experimental group, the control group teaching incorporated more practice with additional examples of chemical reactions, quantitative problems such as balancing equations, solving problems using stoichiometric calculations, etc., which were integrated in the control group lesson plans. Conversely, the experimental group was taught the same material in terms of content while being explicitly introduced to an epistemic discourse that incorporates the three components of the advocated macro–micro–symbolic teaching intervention: (1) explicit teaching at and about the macro, micro, and symbolic levels and the interplay between them, (2) the use of multiple schematic and symbolic representations, such as diagrams, illustrations, drawings, etc. to discuss the three-leveled nature of chemistry, and (3) explicit teaching about models while emphasizing the uncertainty, tentativeness, limitations, creativity, and explanatory nature of models. In what follows, we provide an example of a sample experimental lesson plan to illustrate the nature of the intervention.



*Example of an experimental lesson plan: types of chemical reactions.* The objective of this lesson is to determine the type of a chemical reaction. The teacher begins the lesson by engaging students in a demonstration of some chemical reactions: adding hydrochloric acid to silver nitrate solution. Students are invited to describe the reaction macroscopically focusing on observable changes. Then, using equations, students are encouraged to represent the reaction symbolically relating the macroscopic level to the symbolic level. Students are then asked to interpret their observations microscopically and to use symbols to represent the reaction relating the symbolic level to the microscopic level. Two other demonstrations are performed as well: adding pieces of copper turnings to a solution of silver nitrate and decomposition of $H_2O_2$, and students are asked to repeat the same steps. Afterwards, students are asked to examine the equations that they wrote and compare reactants and products in terms of number, nature, and corresponding change, and then to classify these reactions into: synthesis, decomposition, single replacement, and double replacement. The general form and features of each type are discussed with the students. Generic equations representing the types of reactions are inferred and are presented as models. At this point, the teacher leads a discussion about the nature of models by emphasizing that models are simplified representation of a system, which attend to specific aspects of that system and make them easily visible and communicated to others and which serve specific purposes. This epistemic explanation is centered on the generic chemical equations as a modeling device representing types of reactions. Students are encouraged to use the macro–micro–symbolic triangle (Figure 1) in thinking and in communicating their ideas with an emphasis on the importance of models and modeling to communicate and explain what they observed macroscopically to what happened microscopically, with an emphasis on the descriptive aspect of the macroscopic level and the explanatory aspect of the microscopic level. As a closure, students are invited to summarize the lesson, with an explicit emphasis on the importance of modeling as a tool to communicate and interpret chemical phenomena.

After the teaching intervention, students completed the conceptual chemistry post-test which aimed to reveal students' relational understanding regarding chemical reactions. In addition, students completed the concept map task whereby they represented their knowledge about what happens in a number of chemical reactions. Eight students were interviewed at the end of the teaching intervention to explain their concept maps.

## Data Analysis and Results

### *Quantitative Analysis*

In order to test for the equivalence of the two groups prior to the intervention, means and standard deviations of students' prior achievement scores in chemistry and math were computed. These scores are assumed to reflect respectively students' content competence and cognitive ability. In addition, means and standard deviations of students' scores on the conceptual chemistry pre-test were calculated for both groups. The pre-test was scored by one of the researchers and the teacher independently and any discrepancies were discussed until consensus was reached. These three different scores (prior chemistry achievement, prior math achievement, and pre-test scores) were used as a covariate to account for initial differences between subjects, if any. Results presented in Table 1 indicated that there were no significant differences between the experimental and control groups for chemistry prior achievement scores, math prior achievement scores, and conceptual chemistry pre-test scores ($t = 0.29$ ($p > 0.05$), $t = 0.02$ ($p > 0.05$), and $t = 0.92$ ($p > 0.05$), respectively). Based on these results, it can be assumed that the two groups were equivalent prior to the inception of the study since they started out with relatively equivalent means.

The mean score of all students on the pre-test was 44.96 out of a possible total of 100 ($SD = 16.35$), indicating that students did not have adequate conceptual understanding of the pre-test conceptual chemistry questions. To understand students performance in more depth, pre-test items were categorized into three clusters: pre-test items that target the transition between the symbolic and the microscopic levels and vice versa, pre-test items that address the macroscopic level, and pre-test items that target the transition between the macroscopic and the microscopic levels and vice versa. Scores on each of the three clusters were divided into three ranges: lower third (concept not acquired), middle third (concept acquired at an intermediate level), and upper third (concept acquired). As illustrated in Table 2, results indicate that students faced difficulties with questions that explicitly target the transitions among the levels.

Table 1. Means and standard deviations of the prior achievement in math and chemistry scores and of the pre-test scores

| | Control ($N = 22$) | | Experimental ($N = 24$) | | |
|---|---|---|---|---|---|
| Assessment | *M* | *SD* | *M* | *SD* | *t* |
| Prior Ach. Chem | 73.10 | 16.78 | 71.68 | 16.55 | 0.29 |
| Prior Ach. Math | 70.83 | 17.68 | 70.73 | 17.17 | 0.02 |
| Pre-test | 47.28 | 17.18 | 42.83 | 15.61 | 0.92 |

Prior Ach Chem = Prior achievement score in chemistry.
Prior Ach Math = Prior achievement score in math.
Pre-test = Total score for the conceptual chemistry pretest.

Table 2. Percentages and numbers of students distributed along the continuum 'non-acquired–acquired' on the three dimensions targeted in the conceptual chemistry pre-test

| Pre-test dimensions | Non-acquired % (*N*) | Intermediate % (*N*) | Acquired % (*N*) |
|---|---|---|---|
| Pre-symb-micro | 28 (13) | 57 (26) | 15 (15) |
| Pre-macro | 26 (12) | 33 (15) | 41 (19) |
| Pre-micro-macro | 54 (25) | 41 (19) | 4 (2) |
| Total pre-test | 30.5 (14) | 63 (29) | 6.5 (3) |



Means and standard deviations of the scores on the conceptual chemistry post-test were calculated for the control and the experimental groups. As for the pre-tests, the post-tests were scored by one of the researchers and the teacher independently and any discrepancies were discussed until consensus was reached. Since the groups were assumed to be equivalent prior to the intervention, an independent samples $t$-test was conducted to determine if there was a significant difference between the two groups. A significant difference was indeed found in favor of the experimental group ($t = 0.92$, $p < 0.05$; mean of control group = 63.71/100, mean of experimental group = 75.79/100).

In order to explain the nature of this difference and to identify the possible sources behind it, the sub-scores of items that target the symbolic level, of items that represent a transition between the symbolic and the microscopic levels and vice versa, and of those that represent a transition between the symbolic and the macroscopic levels and vice versa, were calculated and analyzed (Table 3). In addition, a score that represents students' achievement on the quantitative items—items that required calculations—was computed and included in the analysis. No significant differences were found for items that target the symbolic level ($t = 0.14$, $p > 0.05$) and for the quantitative items ($t = 0.69$, $p > 0.05$). Conversely, significant differences were found for items that represent a transition between the symbolic and the microscopic levels ($t = 2.69$, $p <0.05$), and between the symbolic and the macroscopic levels ($t = 3.02$, $p < 0.05$). We attribute these differences to the explicit focus on the nature and characteristics of the relationships among the various representational levels that was central to the experimental teaching condition.

The score on the concept map task consisted of an aggregate score of focus questions and concept map construction. The score on the focus questions represented the sum of scores on questions targeting the macroscopic level, the microscopic level, and the symbolic level. Independent samples $t$-tests were conducted for each of these scores and indicated that there were no significant differences between the experimental and control groups for questions that target the macroscopic level ($t = 1.56$, $p > 0.05$), the microscopic level ($t = 1.70$, $p > 0.05$), and the symbolic level ($t = 0.45$, $p > 0.05$). Moreover, no significant differences were found for the total score on the concept map questions ($t = 1.76$, $p > 0.05$).

Students' maps were scored, based on a scoring rubric adapted from Novak and Gowin (1984) whereby three concept map components are considered: (1) the

Table 3. Means and standard deviations of the scores on the conceptual chemistry post-test for the control and experimental groups

| | Control ($N$ = 22) | | Experimental ($N$ = 24) | | |
|---|---|---|---|---|---|
| Post-test dimensions | *M* | *SD* | *M* | *SD* | *t* |
| Symb-micro | 18.97 | 7.84 | 24.43 | 5.83 | 2.69* |
| Symb-macro | 40.67 | 13.21 | 51.08 | 10.08 | 3.02* |
| Symb | 11.44 | 2.74 | 11.57 | 3.03 | 0.14 |
| Quantitative | 13.71 | 6.22 | 15.01 | 6.40 | 0.69 |
| TOTAL | 63.71 | 18.02 | 75.79 | 16.30 | 0.92* |

*$p < 0.05$.
Symb-micro = Score on post-test items that represent a transition between the symbolic and the microscopic levels and vice versa (the maximum score is 33).
Symb-macro = Score on post-test items that represent a transition between the symbolic and the macroscopic levels and vice versa (the maximum score is 64).
Symb = Scores on post-test items that target the symbolic level (maximum score is 17).
Quantitative = Score for quantitative post-test items (the maximum score is 24).
TOTAL = Total score for the conceptual chemistry post-test (the maximum score is 100).
*Note*. The sum of the total possible scores (17 + 33 + 64 + 24 = 138) is more than 100 since some of the test items were included in more than one of the three score clusters (symb, symb-micro, and symb-macro).

proposition, defined as two concepts related through a connecting phrase, scored from zero to one according to its validity; (2) the levels of hierarchy whereby each level is given a score of three; and (3) the cross-links, which are connections between one segment of a concept to another segment across categories, are given a score of: six if valid and complete, four if valid but incomplete (i.e. with a linking phrase but without revealing the direction of the relationship [or vice versa]), two if valid but with neither linking phrase nor direction, and zero if invalid. Concept maps were scored by one of the researchers and another chemistry teacher and researcher to ensure inter-rater reliability. Discrepancies were discussed until consensus was reached. Results are reported in Table 4. Independent samples *t*-tests were computed for each of these scores and revealed a significant difference between the experimental and control groups for the scores on valid propositions ($t$ = 2.18, $p$ < 0.05) and on the number of cross-links ($t$ = 2.03, $p$ < 0.05), elucidating a significant gain in experimental students' ability to include valid and complete cross-links. However, no significant differences were found for the score on the levels of hierarchy ($t$ = 0.98, $p$ > 0.05). Besides, a significant difference was found ($t$ = 2.19, $p$ < 0.05) for the total score on the concept map construction in favor of the experimental group. Moreover, in total, a descriptive analysis reveals that 22% of the experimental group students were able to generate adequate concept maps as compared to only 4% of the control group students. These striking differences in the results point to the significant gains related to emphasizing an epistemic and ontological approach to teaching the chemistry content in the experimental group. Such emphasis resulted

Table 4. Means and standard deviations of the scores on the concept map construction for the control and experimental groups

| | Control ($N$ = 22) | | Experimental ($N$ = 24) | | |
|---|---|---|---|---|---|
| CM component | $M$ | $SD$ | $M$ | $SD$ | $t$ |
| CM proposition | 7.48 | 3.23 | 10.11 | 4.70 | 2.18* |
| CM cross-link | 13.45 | 21.32 | 28.87 | 28.87 | 2.03* |
| CM hierarchy | 12.00 | 0.00 | 12.52 | 2.50 | 0.98 |
| CM construction | 32.93 | 23.69 | 51.50 | 32.32 | 2.19* |

*$p < 0.05$.
CM = Concept map.
CM construction = Total score on the construction of the concept maps.

in an increased understanding of the changes (macroscopic) and mechanisms (microscopic) involved in the chemical reactions of the concept map task, as well as an enhanced relational understanding as reflected in the experimental students' ability to include appropriate cross-links to relate the various levels.

Figure 3 illustrates the distribution of students' scores in both groups in a box plot diagram. This diagram indicates that the distribution of the control group scores is skewed toward the lower end (right-skewed) reflected in the fact that the mean (33 out of a maximum score of 97.5) is farther out in the long tail than is the median (19.5). In both sets of data, the 25th percentile which is the score at or below which 25% of the students scored is almost the same and is low (close to 18). The main differences between the two plots, however, can be seen in the second and third

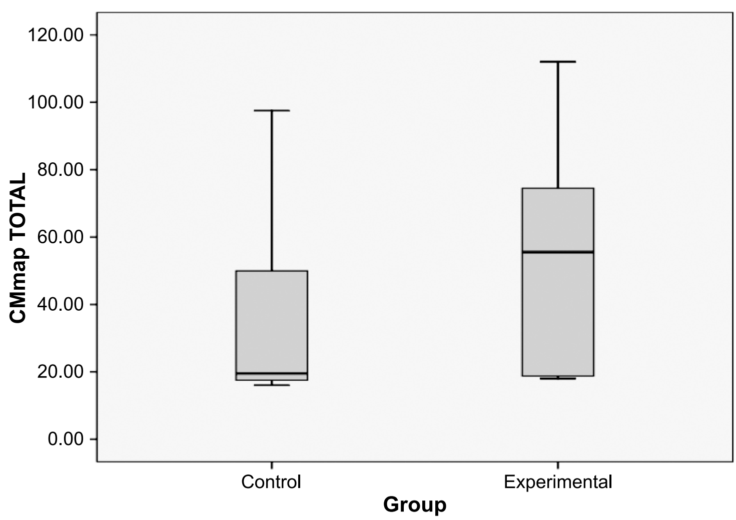



Figure 3. Distribution of students' performance on the concept map drawing task for the control and experimental groups

Table 5. Numbers of experimental and control students distributed along the continuum 'non-acquired–acquired' for each of the post-intervention tasks

| | Non-acquired | | Intermediate | | Acquired | |
|---|---|---|---|---|---|---|
| Task | Experimental | Control | Experimental | Control | Experimental | Control |
| Post-test | 0 | 3 | 5 | 6 | 19 | 13 |
| CM questions | 3 | 5 | 17 | 17 | 4 | 0 |
| CM construction | 10 | 16 | 9 | 5 | 5 | 1 |
| TOTAL | 13 | 24 | 31 | 28 | 28 | 14 |

CM = Concept map.

quartiles, representative of the middle profile. For the control group, the second quartile scores fall between 17.4 and 19.5, and the third quartile scores fall between 19.5 and 52.5. On the other hand, the second quartile scores in the experimental group fall between 18.5 and 55.5, and the third quartile scores fall between 55.5 and 80. These results indicate that the macro–micro–symbolic intervention was mostly responsive to the needs of students who are in the middle of the achievement continuum, since it most effectively improved the performance of these students.

As a summary, numbers of students in the experimental and control groups, distributed along the continuum 'non-acquired (lower end)—acquired (higher end),' are reported in Table 5, for each of the post-intervention tasks: the post-test, the concept map questions, and the concept map construction task. Table 5 shows that a frequency count of the number of responses reflecting acquired skills and relational understanding is 28 in the experimental group; in the control group, it is only 14. Moreover, only 13 responses from the experimental group reflect a poor understanding as compared to 24 responses in the control group. These results indicate again the effect of the intervention on students' relational understanding of chemical reactions.

The quantitative results presented so far provide some evidence that the teaching intervention adopted in the experimental group improved students' conceptual understanding and relational learning as reflected by their significantly higher scores in the post-test and their ability to represent their interrelated knowledge through concept mapping.

### *Qualitative Analysis*

The above quantitative analysis was coupled with a qualitative analysis of students' concept maps and interviews to produce conceptual profiles for these students. The analysis was descriptive in nature and was based on themes that emerged from students' verbal and written productions. This method of analysis is based on the work of Bowen (1994) and Phelps (1994) (cited in Hinton & Nakhleh, 1999) who suggest a qualitative approach when investigating students' individual understanding of chemical concepts. As claimed by Bowen (1994), for this analysis, we only need a small sample, representative of a population, using interviews around instances that probe conceptual understanding, the validity of which is increased as Phelps (1994) argues through the active interaction between the researcher and the students. Accordingly, eight students were purposively selected for this analysis to represent the wide spread of students' performance in both groups. In fact, three students were selected from the experimental section, whose scores on the concept map task fell at the highest and lowest ends and at the median. In the same way, students at the highest and lowest ends were selected from the control group; however, since the median of the control group was very far from the mean, three students were selected to represent the middle profile including two students whose scores are close or equal to the mean score and one student with a score that was a bit higher (close to the experimental group middle score).

In describing students' profiles, three levels were considered: (1) a descriptive level including macroscopic indicators of the reaction, (2) a microscopic interpretation of the chemical reaction, and (3) a symbolic level representation of the reaction encompassing 'conventionally accepted symbols' such as formulas and equations and symbols whose features are shaped by the creativity of their writer. For each level, students' verbal and written productions are categorized as scientifically correct, partially correct, or incorrect. Moreover, a fourth level representing the process was considered which cuts across the three levels presented above, and which refers to a change occurring from an initial state (reactants) to a final state (products). Besides, in order to gain insight into students' ability to relate the three levels, an analysis of the interrelations or cross-links included in students' maps was conducted. These transitions were analyzed in terms of the validity of the connection (appropriate relationship among the levels) between the concepts and the connecting verb used.

To illustrate the above analytical procedure, an example is presented in Figure 4 of a student's concept map from the experimental group. In this map, the student included the three levels of representations as well as cross-links among them. An example of a proposition at the descriptive level includes: indicator of the reaction as formation of precipitate, a correct macro indicator; an example of cross-link from macro to micro is the change of color due to the fact that there is a breakdown of $CuSO_4$ into Cu atoms and $AlSO_4$ aqueous; a valid link between the levels, though not very accurately phrased, is partially conceptually correct. In the interview, the student explains, 'the change in color shows that there is a change in the chemical combination; the microscopic level gives us an explanation of what happened actually.' Moreover, when reflecting on the link between the micro-level and the symbolic drawing, the student said, 'This symbolic representation is a visual aid, personalized, to make us see what happens microscopically.'

The qualitative analysis of selected students' concept maps and interviews led to the formation of different conceptual profiles (High, Middle, and Low), reflective of students' reasoning and understanding of chemical reactions at the macroscopic, microscopic, and symbolic levels and the relations among them, as summarized in what follows:

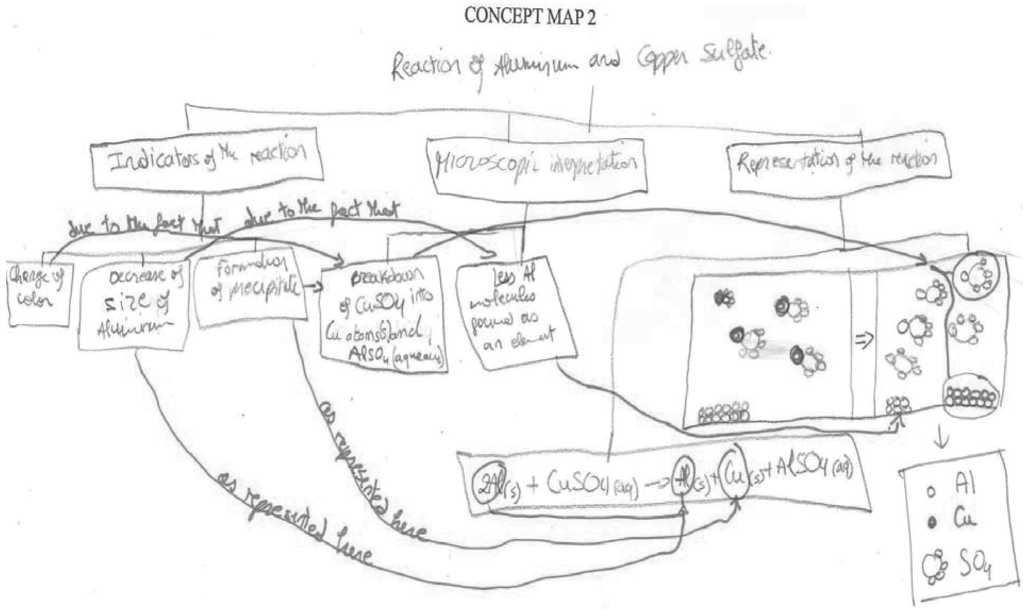



Figure 4. Sample of a student's concept map from the experimental group

(1) The 'High' profile of both experimental and control groups is characterized by a developed level of relational understanding and an adequate epistemological understanding of the three levels, macro, micro, and symbolic, and the relationships among them. However, experimental group students with a 'High' profile demonstrate a more advanced understanding of the microscopic level than control group students. Moreover, they exhibit a notable level of sophistication in making explicit this understanding both in written and verbal productions, easily communicating it using adequate terminology and language. We relate this result to the experimental group teaching's attention to discourse and language that enable students to communicate their understanding while referring to the appropriate descriptors and ways of talking that align with the disciplinary chemistry practices.

(2) The 'Middle' profile exhibits the most noticeable differences between the experimental and the control groups. The 'Middle' profile of the experimental group is characterized by the use of the three levels—with difficulty at the microscopic level—and an ability to make transitions between almost all representations, reflecting some level of relational understanding. Moreover, this profile demonstrates an accurate understanding of the three levels and the relationships among them. Conversely, control group students with a 'Middle' profile use only macroscopic and symbolic representations and confound the microscopic level with the macroscopic level in terms of constructs and language. These students failed to produce meaningful links across the levels revealing an instrumental

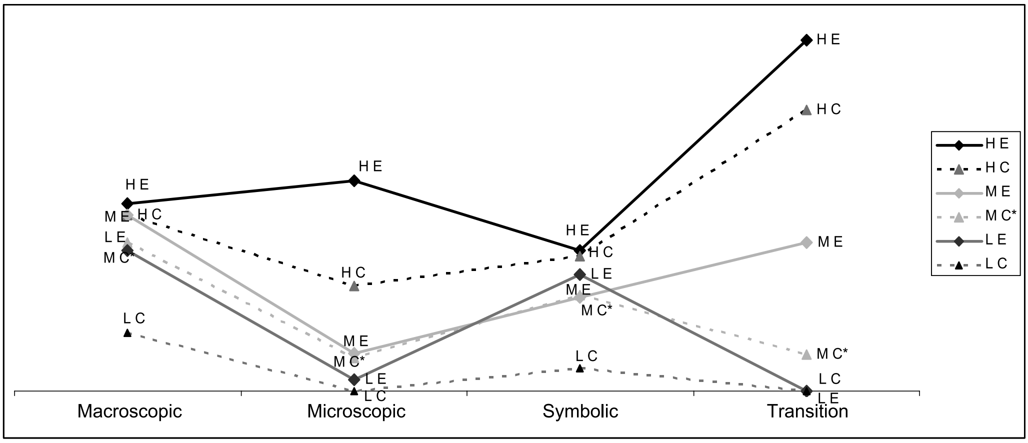
understanding of chemical reactions. Moreover, they failed to articulate an adequate understanding of the scope and functions of the three levels and the relationship among them. These findings reveal that the teaching approach adopted in the experimental group was readily accessible to students who fall in the middle of the achievement continuum, as the most significant differences between the two groups were in fact noticeable in the 'Middle' profile.

(3) The 'Low' profile of the experimental group is characterized by the use of macroscopic and symbolic representations, and the failure to distinguish between the microscopic and the macroscopic levels in terms of constructs and language. Students with this profile fail to produce meaningful links across the levels revealing an instrumental understanding of chemical reactions. Moreover, they fail to articulate a clear understanding of the scope and functions of the levels and the relationships among them. This profile is similar to the 'Middle' profile of the control group with a difference on the relational component. On the other hand, the 'Low' profile of the control group has the following characteristics: most representations are macroscopic; the microscopic level is confounded with the macroscopic level in terms of constructs and language; and students have difficulties while operating at the symbolic level. In addition, students with this profile fail to produce meaningful links across the levels and fail to express any explicit understanding of the epistemological nature of the levels and their relationships. These characteristics of the control 'Low' profile reflect a low level of instrumental understanding of chemical reactions.

The main characteristics of the three types of profiles, 'High,' 'Middle,' and 'Low,' for both the experimental and the control groups, are represented graphically in Figure 5. As illustrated in Figure 5, the main differences between the high profiles of the control and the experimental groups stem from their performance at the microscopic level and the transitions between the levels. On the other hand, the main difference between the control and experimental middle profiles is in the transitions between the levels. Lastly, the differences between the control and experimental low profiles can be accounted for by the gaps in performance at the macroscopic and the symbolic levels. However, both of these low profiles lack transitions between the levels. Moreover, it is important to note that the low profile representing the experimental group is relatively similar to the middle profile representing the control group regarding the macroscopic, microscopic, and symbolic levels. In sum, comparing experimental and control students' profiles of the same level leads to the conclusion that the teaching intervention adopted in the experimental group enhanced students' relational understanding of chemical reactions, and was mostly responsive to middle level achievers.

## Discussion and Conclusions

This study adds to the body of literature that highlights the inherent teaching and learning difficulties related to the abstract nature of chemistry as a discipline (e.g.




H E = High profile for the experimental group.
H C = High profile for the control group.
M E = Middle profile for the experimental group.
M C= Middle profile for the control group.
L E = Low profile for the experimental group.
L C = Low profile for the control group.
*The middle profile for the control group is represented by a composite score of students who performed close to the mean, equal to the mean, and a bit higher than the mean since the distribution is skewed toward the lower end (right-skewed).

Figure 5. Categories of experimental and control students' conceptual profiles along the micro, macro, symbolic levels and transitions between them

Gabel, 1998; Johnstone, 1991, 2000; Treagust et al., 2003). At the beginning of the study, the majority of students exhibited difficulties related to the transitions between the macro, micro, and symbolic levels while solving conceptual chemistry problems, as revealed by pre-test results. This finding is consistent with previous studies conducted with middle-school, high-school, and college students across diverse educational and linguistic contexts such as France (e.g. Cokelez, Dumon, & Taber, 2007), Finland (e.g. Ahtee & Varjola, 1998), Israel (e.g. Dori & Hameiri, 2003), Greece (e.g. Stavridou & Solomonidou, 1998), the United Kingdom (e.g. Brosnan & Reynolds, 2001), and the United States (e.g. Hinton & Nakhleh, 1999). We suggest that the teaching intervention adopted in the experimental group addressed some of these difficulties as it enhanced students' conceptual and relational understanding of chemical reaction, as evidenced by the post-intervention findings. In sum, based on the findings of this study we present four assertions that characterize our findings. We emphasize that, while the three first assertions align with and support previous findings documented in the literature, the main contribution that our study adds to the chemistry education research field resides in the fourth assertion, which highlights the significance of a macro–micro–symbolic teaching approach to promote relational understanding in chemistry.

*Assertion 1. Most Students were Able to Interpret Chemical Reaction at the Macroscopic Level*

Students in both control and experimental groups were able to adequately address macroscopic-level questions. This is reflected mostly in the qualitative analysis of students' reasoning in the concept map task and interviews as students were able to attend to changes in phenomenological properties of substances involved in chemical reactions. Examples of macroscopic observations include 'a black solid is formed,' 'mass seems to have been increased' (Concept map 1, focus question), and 'these are indicators [of a reaction] since once heat is generated and the wool starts burning, it indicates that a reaction is happening' (Interview 3). Hence, students were able to detect the macroscopic changes in chemical reactions, which resonates with previous findings in the literature (e.g. Cakmakci, Leach, & Donnelly, 2006; Hinton & Nakhleh, 1999).

*Assertion 2. A Major Impediment to Conceptual Understanding can be Attributed to Students' Inappropriate Application of Macroscopic Reasoning to Explain Phenomena at the Microscopic Abstract Level*

This assertion is based on the finding that many students exhibited a macroscopic/microscopic level confusion while responding to test items that target the microscopic level. Moreover, this claim is supported by students confounding terminology that belongs to the macroscopic realm with their microscopic reasoning and explanations, such as interpreting the decrease in the size of the metal sheet as a result of the shrinking of the molecules. The profiles of the 'Low Control,' 'Low Experimental,' and 'Middle Control' present a clear basis for this assertion. This finding is consistent with the results of Johnson (2002) and Gómez Crespo and Pozo (2004). In fact, the directionality of commonsense reasoning from the observable (macro) to the inferential (invisible/micro) might be related to students' propensity to apply their macroscopic reasoning to make sense of abstract and inaccessible microscopic phenomena.

*Assertion 3. Students Tended to Exhibit Difficulties in Understanding the Epistemic Nature of Models*

The challenge students seem to face when they are asked to reflect on the scope and function of the symbolic and microscopic levels, and when they operate at the abstract microscopic level, is suggestive of an inadequate understanding of the nature and role of models. These difficulties were demonstrated clearly in both quantitative and more qualitative. As reflected in the profiles corresponding to 'Low Control,' 'Low Experimental,' and 'Middle Control,' students were particularly challenged when asked to explain the functions, nature, and affordances of the symbolic and microscopic levels as far as modeling is concerned. Rather than viewing models as human constructions that are tentative explanations with predictive power that illustrate abstract concepts, students tended to perceive models as exact copies of reality. Students seemed to consider models as the source of 'truth' rather than as tools to enable a simplified representation of reality and as tools for reasoning. Again, similar findings are reported by Gómez Crespo and Pozo (2004) and Cakmakci et al. (2006).

*Assertion 4. Students' Relational Understanding can be Fostered by an Explicit Teaching of the Nature of Chemical Knowledge in Terms of Macro, Micro, and Symbolic Realms and the Relations Among Them*

As illustrated by the post-test results, the majority of students in the experimental group developed adequate relational understandings of chemical reactions as compared to approximately half of the students in the control group. Moreover, 22% of the experimental group students were able to generate adequate concept maps, with significant numbers of accurate cross-links among the levels, as compared to only 4% of the control group students. These differences in the two groups' performance can be explained by the fact that students in the experimental group were trained to think about concepts at the micro, macro, and symbolic levels, first discretely, and then relating them together. Moreover, students were also trained to think about the nature of the three levels and the relationships among them. We suggest that by understanding the nature of chemical knowledge, its foundations and structure, students gain an epistemological awareness of chemistry as a discipline. This epistemological appreciation, coupled with a conceptual approach to teaching and learning chemical reactions, seemed to promote relational understanding of chemical phenomena. Conversely, by focusing on the three constructs at the different levels separately, without paying additional attention to the interrelations between the levels and without explicitly addressing the nature of chemistry as a discipline, students in the control group were not able to develop adequate relational understanding of chemical reactions. Hence, this assertion suggests that training students to transform their acquired knowledge within and across various representational forms and to reflect on the scope and function of each level fosters their relational reasoning hence helps them develop a more integrated conceptual knowledge in chemistry. This assertion motivates pedagogical approaches that consider not only content regarding the three levels and their interrelations, but also the epistemic and ontological underpinnings of chemistry as a discipline to provide students with tools to organize their chemical knowledge according to disciplinary ways of knowing in chemistry, and to promote their appreciation of modeling and representations that surround chemistry as a field. Accordingly, the findings of this study contribute significantly to our understandings of the nature of learning in chemistry and to ways in which this learning can be better served through pedagogical approaches that foster disciplinary reasoning practices in chemistry.

In view of the study findings, it is hypothesized that one of the impediments to students' understanding of chemical reactions is rooted in the structure and reasoning underlying these understandings. As suggested by Chi (1992), knowledge can be classified into three major ontological categories: matter, processes, and abstractions, each with characteristic attributes that distinguishes it from the others. Chi (1992) argues that it is very hard to accomplish conceptual change across ontological categories. As suggested by Chi (2005), processes could belong to two ontologically different types: emergent and direct. Chi (2005) explains that misconceptions related to emergent processes are robust since they often result from misconceiving these processes as direct, and hence attributing to them the commonsense understanding of direct processes. In the case of chemical reactions, students might misconceive chemical change as a ‘direct linear,’ rather than an ‘emergent interactive’ process.

The question is then why was a relational understanding of chemical reaction more developed in the experimental group than in the control group? In light of the explanation above, we might suggest that the macro–micro–symbolic teaching of chemical reactions provided students with an alternate framework for their ontological knowledge to construe chemical change as an emergent process. Therefore, by emphasizing the interactive nature of this change and accounting for macroscopic indicators by the collective outcome of random microscopic interactions, and by explicitly analyzing the relationships between the patterns (the macro) and the constituent level (the micro), this teaching approach seemed to present students with a structure, ‘the emergent process schema’ (Chi, 2005) to which they can shift their representations and reasoning. Therefore, it might be hypothesized that by modifying students’ ontological knowledge through this ‘ontological shifting,’ the macro–micro–symbolic teaching approach fosters conceptual and relational understanding. This hypothesis remains to be validated with further research.

### *Implications*

The findings of the study offer implications that can inform practice, implications that are drawn from the direct findings as well as from the close interactions and ongoing reflective discussions that resulted from the dynamics of the partnership between one of the researchers and the chemistry teacher involved in this study. The main implications are summarized in what follows.

The study findings motivate the adoption of a macro–micro–symbolic approach to instruction. Optimally, chemistry instruction at and about the three levels should become a habit of mind or namely a ‘habit of teaching chemistry,’ so that it becomes internalized by teachers, hence reflected in their lesson planning, classroom interaction, and assessment. Apparently, being engaged in this research promoted such an attitude in the collaborating teacher’s approach to chemistry. This is illustrated in the following excerpts from the reflections he wrote a few weeks after the study was conducted:

> The link between the three realms has become an intrinsic concern that I find myself unconsciously addressing when I plan my instruction. I am starting to feel that a comprehensive and conceptual understanding of any concept cannot be achieved except by emphasizing the link between the three levels.

in order to adopt a macro–micro–symbolic teaching in their classrooms, chemistry teachers need to be trained on planning lessons and implementing instruction accordingly. Therefore, teacher preparation programs ought to be designed to promote teachers' pedagogical content knowledge in this aspect. This can be fostered by developing teachers' knowledge of the teaching difficulties and the student learning difficulties that are directly related to the three-leveled nature of chemistry. Therefore, teachers should become aware of their own reasoning about the macroscopic and microscopic meanings and how they translate these meanings to students using clear and precise language.



### *Recommendations for Research*

Findings of this study suggest that developing students' relational thinking can be fostered by their appreciation of the epistemological and ontological nature underlying the structure of chemical knowledge, which can be developed through carefully planned instruction. This might imply that sophisticated metacognitive reasoning about chemical knowledge helps students to conceptually integrate the macro, the micro, and the symbolic levels thus lead them to develop interrelated and sophisticated conceptual structures characteristic of relational understanding. This issue promises to be an interesting area of future research. The present study was conducted within a limited context and for a short period of time. Additional studies in different contexts, covering different topics in chemistry and at different grade levels would make generalization of the study findings more legitimate. Moreover, future research is needed to understand the effect of the various components of the intervention adopted in this study on student learning by focusing on factors such as the interplay between the macro, micro, and symbolic levels, the use of various schematic representations, and explicit teaching with and about models. This should be done with larger groups of students and over longer period to provide students with many opportunities to master the concepts studied, appreciate the epistemological nature of chemistry, and acquire its tools and language, for each of the macro, micro, and the symbolic levels. Moreover, research might focus on exploring the development and progress of students' conceptual understanding over time regarding the concept of chemical reaction. In this way, researchers can attend to the developmental aspect of conceptual understanding in response to teaching, and hence identify factors and mechanisms that might assist or hamper students' cognitive growth and suggest recommendations for improving instruction in light of these findings.

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**Appendix**

*Sample Questions from the Pre-test*
*Sample 1*:
*Content: Structure and properties of matter, kinetic energy*

- *Macroscopic level*
- *Relating the macroscopic level to the microscopic level*

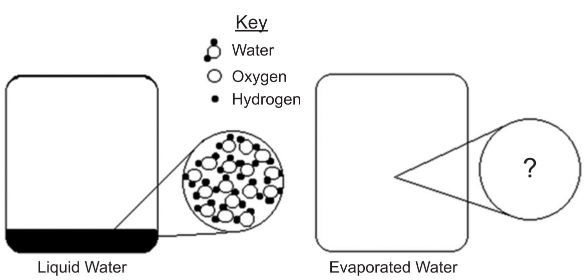
Propose a microscopic explanation for what is happening when you use a tea bag to make a cup of tea. Begin by defending your explanation with as many macroscopic observations as possible.

a. Observations:
b. Explanation:

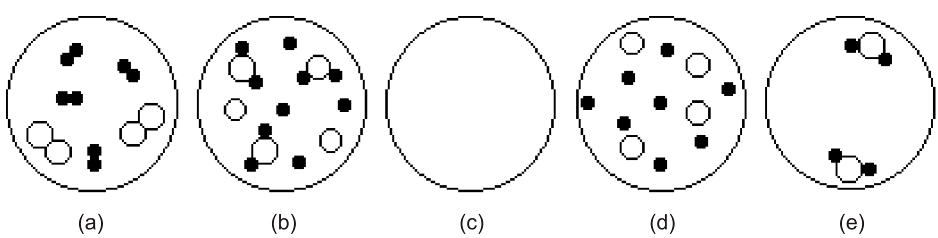
*Sample 2* (adapted from Mulford, 1996):
*Content: Structure and physical change of matter*

- *Relating the symbolic level to the microscopic level*

The circle on the left shows a magnified view of a very small portion of liquid water in a closed container.




What would the magnified view show after the water evaporates?




Briefly explain your answer.

*Sample Questions from the Post-test*

*Sample 1*:
*Content: Conservation of matter in chemical reactions*

- *Relating the symbolic level to the macroscopic level*
- *Relating the symbolic level to the microscopic level*

Take some time to understand the two illustrations below (illustration A and illustration B)

Illustration A:

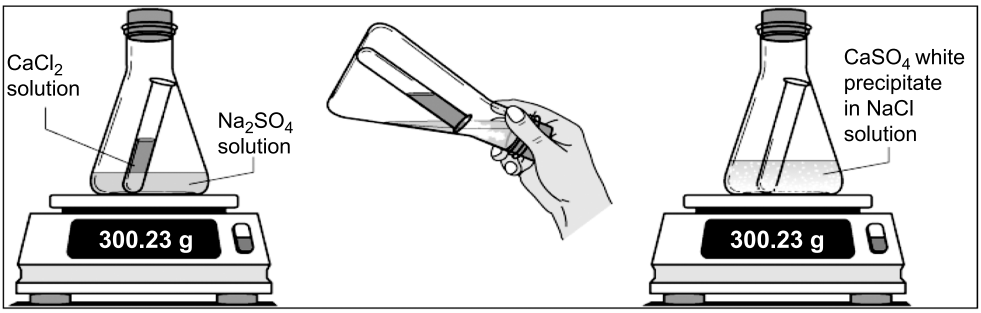
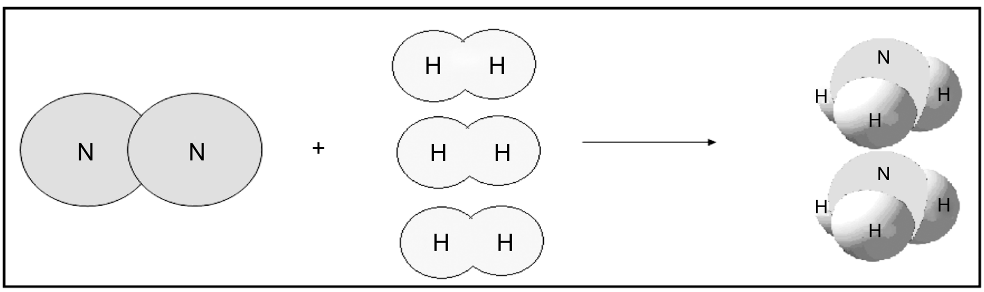



Illustration B:




Reactant side: 2N and 6H

Product side: 2 N and 6 H

The two illustrations (A and B) above demonstrate the law of conservation of matter.

1. Describe how each of the two illustrations (illustration A and illustration B) demonstrates the law.
2. Imagine that you work in a factory in the field of industrial chemistry and that you need to explain to your colleagues the law of conservation of matter during chemical processes. In your explanation, you need to outline the reason behind this law. Which of the two illustrations above (A or B) would you make use of? Explain your choice.

*Sample 2* (adapted from Salloum, 2000):

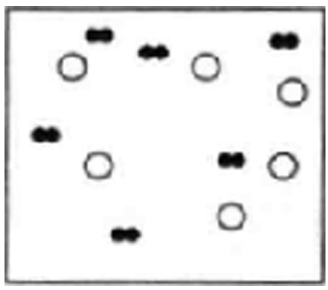
*Content: Reaction equation, stoichiometry and properties*

- *Relating the symbolic level to the microscopic level*
- *Relating the symbolic level to the microscopic level quantitatively*
- *Relating the symbolic level to the to the macroscopic level*

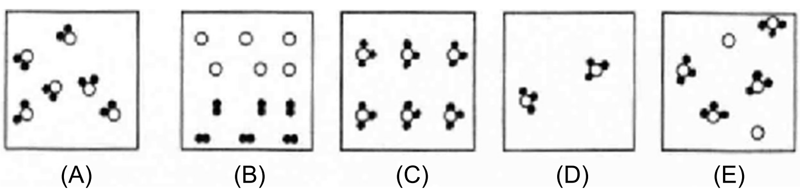
Two substances, A and $B_2$, in the gaseous state react under appropriate conditions based on the following equation:

$$2A_{(g)} + 3B_{2(g)} \rightarrow 2AB_{3(g)}$$

A is a yellow gas and both $B_2$ and $AB_3$ are colorless gases. A and $B_2$ are mixed together in a closed glass container, in the proportions represented in the figure below.



The reaction between A and $B_2$ is allowed to take place. Which of the boxes below represent the content of the container after the reaction takes place?




1. Explain your answer.
2. Assuming that the container is transparent (see-through), what would the inside of the container look like? Explain.