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Assessing Students' Molecular-Level Representations of Solution Chemistry

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Abstract: In this study, university students were provided with repeated opportunities to represent their ideas graphically, and to examined via their drawings the extent to which they could visualize macroscopic phenomena microscopically. These drawings provided insight into the students' basic understanding of solution chemistry, revealing three conceptual models: the *Undifferentiated Symbolic Model,* the *Particulate Model,* and the *Symbolic Ionic Model.* Generally speaking, students who had poor conceptual understanding tended to exhibit the Undifferentiated Symbolic Model, whereas students with deeper understanding tended to employ the Symbolic Ionic Model. Students' conceptual comprehension was predictable from their graphical representations, which better elucidated what they actually comprehended about the phenomena, as opposed to their ambiguous verbal descriptions alone. The results of this study demonstrated a lack of development in university students' conceptions of solutions. Their weakness in understanding at the molecular-level became more obvious when they were asked to represent their ideas in drawings. Few students exhibited expert knowledge, and several common misconceptions were found, which indicated typical difficulties students have perceiving common phenomena at the molecular level. The findings of this study illustrate how eliciting graphical representations can be used to assess students' conceptual understandings.

Key words: Molecular-level understanding, Graphical representations, Solutions chemistry, Assessment.

I. Introduction

Solution chemistry, one of the basic topics in chemistry, requires understanding a variety of concepts, including the particulate nature of matter (Driver, 1985; Driver *et al.,* 1994; Gabel *et al.,* 1987; Nussbaum, 1985; Pozo *et al.,* 2005), interactive and dynamic aspects of chemical reactions (Ben-Zvi *et al.,* 1987; Boo & Watson, 2001; Fensham & Fensham, 1987; Stavridou & Solomounidou, 1989), and chemical and physical changes (Cosgrove & Osborne, 1981; Prieto *et al.,* 1989; Schollum, 1981). In order to better understand solution chemistry, students need an integrated knowledge of these concepts both at the macroscopic and molecular levels. However, many have difficulty in developing integrated understanding, and their prior knowledge containing alternative conceptions seem to be difficult to change (Ebenezer & Erickson, 1996; Ebenezer & Gaskell, 1995; Posner *et al.,* 1982; Raviolo, 2001). This paper reports the results of an assessment of university students' molecular-level representations in solution chemistry as a demonstration of their molecular-level understandings.

Representation skills are critical for scientists to solve problems, investigate phenomena, and communicate with other scientists. Chemistry, in particular, is a visual science, and visualizaton plays a major role in chemists' daily practices. Chemists investigate natural phenomena through ideas and images of molecules, atoms and subatomic particles, and the relationships amongst them. In order to support these practices, chemists have developed a variety of representations including molecular models, chemical structures, formulas, equations, and symbols. The ability to comprehend the representations used by scientists is therefore an important part of learning science (Kozma *et al.,* 2000; Roth & McGinn, 1998). There is a growing recognition in science education research that science is a combination of multi-modal

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forms of representations including linguistic, numerical, graphical, and tabular modes (Lemke, 2001; Unsworth, 2001). This means that learning science involves understanding different representations of science concepts and processes, being able to translate them into one another (Kang & Noh, 2006; Kang *et al.,* 2005). Yet, students' understanding and proper use of representations are not well supported in science classrooms (Wu *et al.,* 2001). Many students are not capable of providing equivalent representations for a given representation because of a lack of content knowledge or a lack of visuospatial thinking skills (Kozma & Russell, 1997). In particular, translation between representations is an information processing task that requires knowledge of the underlying concept (Keig & Rubba, 1993) and the conceptual knowledge allows students to interpret the information provided by the initial representation and infer the details to construct the target representation (Lesh *et al.,* 1987).

Wu and Shah (2004) reported that previous studies have identified three major alternative conceptions that arise from difficulties in comprehending and interpreting representations; (1) representing chemical concepts at the macroscopic level rather than the microscopic or symbolic level; (2) comprehending visual representations at the macroscopic level and by surface features; and (3) interpreting chemical reactions as a static process. Whereas chemists use both macro- and molecular-level representations of phenomena in problem solving situations, research indicates that students have difficulty in using appropriate representations when solving problems in science (Bowen, 1990; Noh & Scharmann, 1997), and connecting symbolic, macroscopic, and molecular levels of representation (Gabel, 1998; Keig & Rubba, 1993; Krajcik, 1991; Nurrenbern & Pickering, 1987; Yarroch, 1985). Previous studies also have found that although chemistry textbooks frequently presents symbolic and microscopic representations, many secondary school students show difficulties in applying ideas of particles and constructing microscopic representations to make explanations of observation (Brosnan & Reynolds, 2001; Griffiths & Preston, 1992; Renstroem *et al.,*

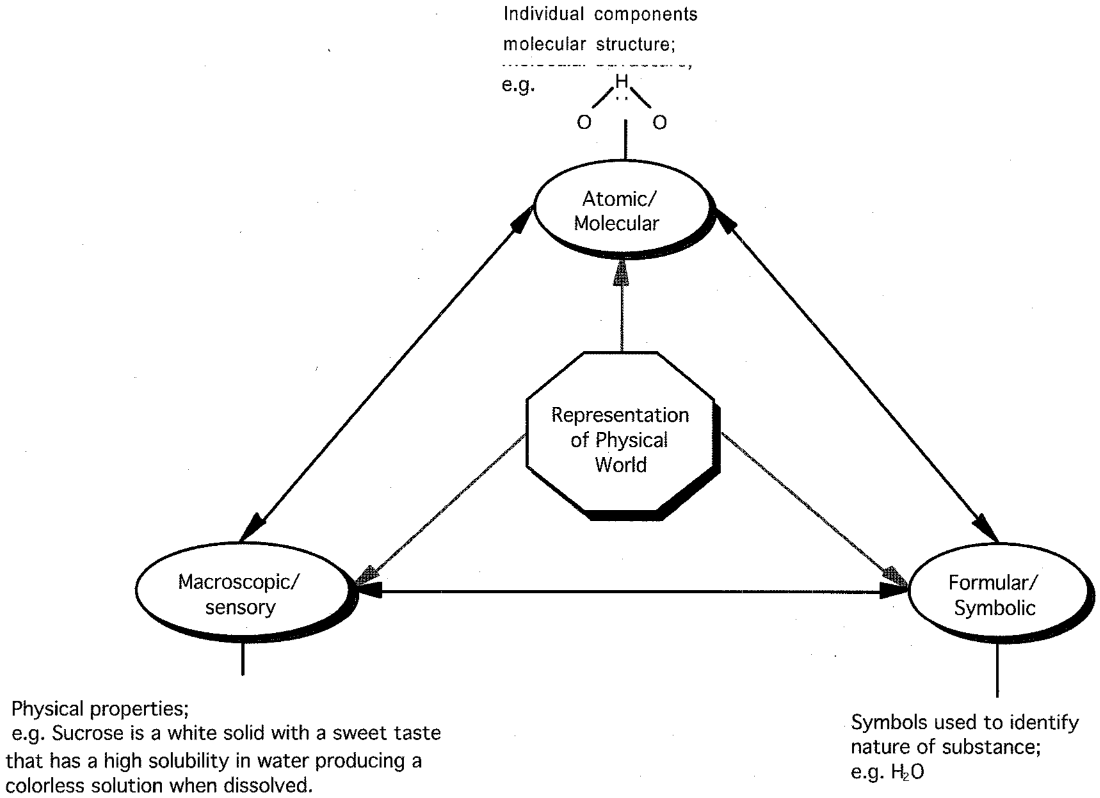

Fig. 1 Types of Representations for Understanding Chemistry (Adapted from Johnstone (1992), p. 78)

1990). Moreover, while chemists view a chemical reaction represented by an equation as an interactive and dynamic process, students often can only construct a static model of it.

Johnstone (1982, 1991) proposed that competency in chemistry required three levels of representation: sensory (or macro), atomic/molecular (or sub-micro), and symbolic (see Fig. 1). Most problem solving encountered in chemistry classes, however, simply requires students to deal with symbols in an algorithmic manner (Ault, 2001). Students consequently appear to lack atomic-/molecular-level understanding both when they observe chemical phenomena and are required to solve problems. Students also have trouble in connecting what they observe in the laboratory with their notions of microscopic entities and processes (Gabel, 1998; Nurrenbern & Pickering, 1987; Yarroch, 1985).

Several studies have attempted to encourage students' understanding at the molecular level. For example, Gabel and colleagues (Gabel, 1993, 1998; Gabel *et al.,* 1992) argued that among the three levels of understanding − sensory, symbolic/formula, and atomic/molecular− an approach from the atomic/molecular level can be more effective in helping novices to understand the concept of matters as discrete particles while also fostering comprehension on the symbolic and sensory levels. To support students' development of chemistry understanding, some studies have suggested facilitating the particulate representations of the particles in a chemical reaction (Laverty & McGarvey, 1991; Noh & Scharmann, 1997; Singer *et al.,* 2003). Other studies have been conducted to investigate the effect of molecular-level representation and animations on students' visualization of chemistry concepts and processes, especially the dynamic behavior of particles in three dimensions (Burke *et al.,* 1998; Sanger & Greenbowe, 2000; Schank & Kozma, 2002; Williamson & Abraham, 1995). These studies support the importance of molecular-level understanding and representations in chemistry learning.

It is still rare for students in a typical chemistry class to visualize their ideas in drawings except some experimental studies where researchers designed new instructional methods to integrate drawings and writings. For example, Kang and Noh (2006) investigated the influence of situational interest, attention, and cognitive effort on drawings as a method to assist middle school students to connect and integrate multiple external representations when they were taught through drawing. Han *et al.* (2006) examined the effects of drawing and analyzing pictures instruction in 7th grade chemistry classes in the development of conceptual learning of the particulate nature of matter. While these studies have found the relationships between multiple external representations and its impact on students' conceptual understanding, attention, and interests, these were limited in K-12 settings. There is little research conducted with university-level students involving whether older students who posses higher-level of conceptual understanding than middle or high school students still lack ability to visualize their understanding and make connections between different representations. Before designing a new instructional approach to integrate drawings and writings in traditional chemistry instruction for university students, this study investigated to what extent university students were able to represent their conceptual understandings in drawings as a way of assessment rather than an instructional practice. The students in this study were provided with repeated opportunities to represent their ideas graphically through drawings. The drawings were then examined in order to determine students' general understanding of solution chemistry as indicated by the extent to which they could visualize macroscopic phenomena microscopically. This study aimed to illuminate the students' conceptual understanding of solution chemistry in two different representational systems: verbal descriptions and graphical drawings. Since molecular-level representations require students to visualize images beyond text descriptions, the students were asked to draw their ideas as well as verbally describe them.

II. Methodology

This study was part of a larger study examining the influence of the use of a hypermedia program to support students' understandings of basic chemistry concepts. Students participating in this study were from an introductory chemistry course (n ≈ 400) at a large research university in the Midwest, USA. A stratified random sampling technique was used to select a target group of twelve students for intensive data collection. The target group was selected using data reported by the students on a questionnaire administered early in the course reflecting the variation among students with respect to their performance in previous math and science courses in high school and experiences with computer technology. All participating students were ranked on the basis of a total score for their math/science background (number of courses x grade in each course) and divided into three groups. Within each group, students were then designated as high or low with respect to their technology expertise and numbered consecutively based upon that sub-grouping. Four students from each group (based on math/science background) were then randomly selected for participation in the interviewing resulting in two students who were weak and two who were strong with respect to technology/computer experience being included in each. As a result, the target group was comprised 12 students ranging from weak math/science background and weak technology experience to strong math/science background and strong technology experience.

This study investigated the graphical representations and verbal descriptions that students employed to explain physical and chemical reactions involving various solutions. The primary research questions were:

(a) How do students graphically represent common chemical phenomena or solution chemistry at the molecular level?
(b) What do the graphical representations reveal about students' understanding?

Interview protocols were developed by a team of experts including chemists, science educators, and chemistry professors using elements of an approach in which students predict, observe, and explain phenomena related to the concepts of interest with some guidance provided by the interviewer using a Dynamic Science Assessment method (Lee, 2005; Magnusson *et al.,* 1997).

To assess students' molecular-level representations, various phenomena related to solution and precipitation were introduced to students. The students were then asked to (1) draw what they pictured in their mind, and (2) explain their observations and thinking (adapted thinking-aloud protocol, Randell, 1995). Additional questions were asked in many cases to prompt students to clarify their drawings and vague verbal statements.

Each interview lasted about 90 minutes, and all of the interviews were videotaped and transcribed for further analysis[1]. A list summarizing the interview segments used in this study follows (also see Appendix for sample interview questions):

- Introduction: *The Language of Solution Chemistry* – Participants were asked general questions about the nature and definition of solution, solubility, and dissolving.
- Phenomenon 1: *Solutions and Concentration* – Participants were shown three different concentrations of potassium dichromate ($K_2Cr_2O_7$) in test tubes, one of which was saturated with visible precipitate at the bottom. Interview questions targeted students' understanding of solubility and concentration, and dynamic equilibrium.
- Phenomenon 2: *Solubility with Solid Solute* – Participants were shown three beakers containing the same amount of water and solute of sodium chloride ($NaCl$), sodium nitrate ($NaNO_3$), and potassium nitrate (KNO_3). The sodium chloride and potassium nitrate solutions were saturated with visible undissolved solute at the bottom of each beaker as a result of solubility differences.
  - *Part 1* – Participants were asked to describe each solution and were asked regarding the concepts of "saturation" and "solubility product."
  - *Part 2* – Solutions were heated, and participants were asked to account for observed changes in visible undissolved solute. Interview questions concerned the relationship between temperature

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[1] Due to a technical problem in transcription, transcriptions of only nine student interviews were completed and included in the analysis. In terms of students' background profiles; there was no significant pattern found between the nine students who were included in the final analysis and the rest.

and solubility.

- Phenomenon 3: *Solubility and Precipitation* – Participants were asked to predict what would happen when they mixed barium chloride ($BaCl_2$) with sodium nitrate ($NaNO_3$) and sodium sulfate (Na_2SO_4) separately, and to write a balanced chemical equation representing the predicted reactions (chemical formulas were provided to the participants). Students observed the interaction of the substances and discussed issues of solubility and precipitation.

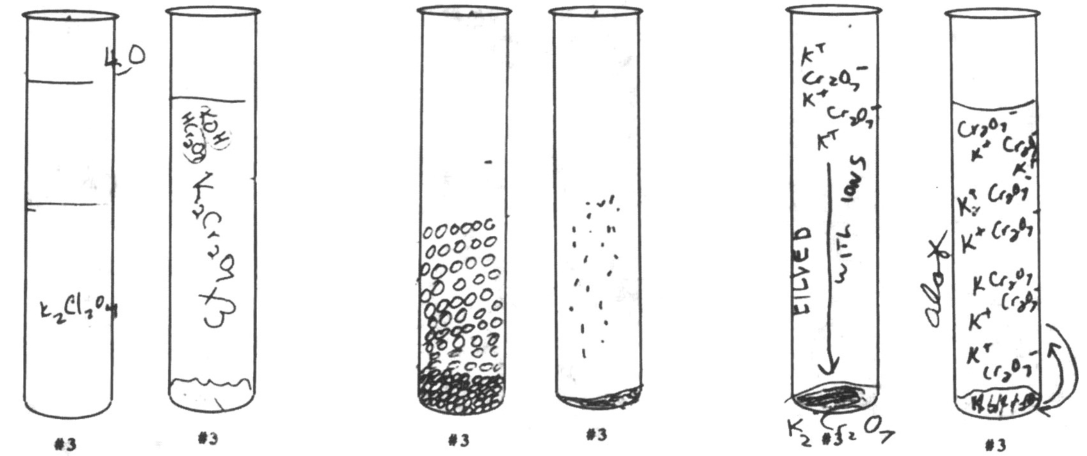
All interviews were transcribed and coded for the level of students' conceptual understanding along with their drawings. Students' drawings were analyzed to find emerging patterns using a qualitative methodology. Then, the drawings were categorized by characteristics that represent particulate and molecular concepts.

Students' verbal descriptions were transcribed for further analysis and coded for grouping with one of the target concepts as described above. From these transcriptions and students' drawings, our research team developed interpretations of the meanings of the statements as well as the drawings. A consensus was reached on several areas of analysis: drawings of students' representations of a phenomenon, the verbal descriptions and explanations, the specific language use of students, and students' general level of confidence in these representations.

The data were analyzed using an emergent content analysis approach, which is a form of content analysis (Miles & Huberman, 1994; Weber, 1990), since the purpose is to capture the content of what is represented by students. The emergent representations of students' understandings resulted from a recursive process of constructing, comparing, and refining specific descriptions of students' ideas from task to task, as well as in comparing students' ideas to currently accepted scientific knowledge.

The first step of the analysis was to underline any data (e.g., text or diagrams) that provided insights about student's ideas in relation to the targeted concepts. The second step was to determine the conceptual areas about which the underlined sections provided insights. For example, every time students said or drew something that indicated his or her views about the particulated nature of molecules, it would be marked or "coded". After coding was completed, similarly-coded sections were compiled, and the process of creating representation of the information began.

Students' drawings of individual phenomena were categorized based on whether elements of the solution were represented in molecular or symbolic terms and whether ions were depicted. Three model categories from the drawings were identified: Undifferentiated Symbolic, Particulate, and Symbolic Ionic models. Fig. 2 shows customary drawings in each model category.



(a) Undifferentiated Symbolic Model (b) Particulate Model (c) Symbolic Ionic Model

Fig. 2 Types of Student Graphical Representations

III. Results & Discussions

Differences and changes in understanding and representations occurred with all of the students throughout the interview. The interview process provided repeated opportunities for participants to convey their ideas, which also afforded them the ability to revise or alter them. The conceptual models that represent students' drawings and understanding will be reported first; then, changes in students' understanding across the phenomena will follow.

1. Types of Student Graphical Representations

1) Undifferentiated Symbolic Model

Students' drawings in this model type depicted solutions according to their chemical formulas, e.g., $K_2Cr_2O_7$ contained in a test-tube. The drawings did not indicate particles of either solute or solvent. Because they did not depict the solution in particulate terms, it was difficult for students to visualize the differences among test tubes with different concentrations of the same solution. Students who adapted the other two models in their visual representations, however, illustrated different concentrations by different numbers of solute particles. For example, they represented distinctions by using symbolic indications (e.g., $K_2Cr_2O_7$ x 2 or $K_2Cr_2O_7$ x 3) or by drawing different levels (or heights) of separate solute lines.

Students who employed the Undifferentiated Symbolic Model generally evidenced little understanding of solution chemistry. Throughout the interview, one of the participants named *Lee*[2] exemplified the conceptual thinking common to students who used this model type, which lacked a grasp of solubility and precipitation. When *Lee* was asked about dissolving, she answered "If they dissolve? The molecules are mixed up (Le S/P: P1, L24[3])." She could not provide additional elaboration. Moreover, when she encountered the real phenomenon, she failed to represent her previous notion of "mixed up", instead she drew separate lines between the solute substance and water (see Fig. 2a). Thus, she did not initially exhibit any molecular-level comprehension of solution and dissolution.

2) Particulate Model

Students' drawings reflecting the Particulate Model depicted a solution by rendering it as dispersed particles; that is, circles or dots in the drawings (see Fig. 2b). These students seemed to at least comprehend the particulate nature of matter; however, some of them exhibited alternative understanding of the nature of solution or dissolution. For example, when asked about solution and dissolution in general, *Monica* demonstrated confusion about the dissolving and melting process:

> Interviewer: When something dissolves, what do you picture occurring?
>
> Monica: For example, if you have a glass of water and you put salt in it, the solute almost ... melting is not the correct word, but dissolving into the solution is another comparable word ... is, it's like melting into the solution, combining with the water. So it makes a solution of salt and water... It just gets smaller.
>
> [Mo. S/P: P1, L39-46; P2, L52]

Despite *Monica's* statement that "melting is not the correct word," she appeared to perceive the dissolving processes as similar to an ice cube melting – its size decreases as time passes. No understanding of dissociation was evident in her drawings or verbal descriptions. This kind of confusion has frequently been witnessed in previous research with younger children (Cosgrove & Osborne, 1981; Driver, 1985; Ebenezer & Erickson, 1996; Prieto *et al.,* 1989; Schollum, 1981).

Monica's second drawing also seemed to illustrate the appearance of crystals on a more macroscopic level rather than molecular level. She tried to show a different shape of crystal as circles for each precipitate such that potassium nitrate appeared longer (i.e., oval rather than circle) than the other two. However, she also depicted sodium nitrate particles, although the solution was clear and lacked a precipitate. This suggests that she thought that the dissolved, invisible particles maintained the same structure as the undissolved solid. This observation mirrors the results of Ben-Zvi *et. al.*'s study (Ben-Zvi *et al.,* 1987).

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[2] Names used in this paper are all pseudonyms.

[3] Le=Interviewee's name code; S/P=Solution and Precipitation task; P1= Paragraph no. 1; L24= Line no. 24

3) Symbolic Ionic Model

The third category of model identified from students' drawings was the Symbolic Ionic Model. These drawings contained illustrations of cations (e.g., K^+) and anions (e.g., $Cr_2O_7^-$) as the result of dissociation in solutions (see Fig. 2c). Unlike the Particulate Model, students did not characterize particles as circles or dots. Instead, precipitates at the bottom of a test-tube were depicted as more closely spaced or clustered particles, and they were represented with a molecular formula (e.g., $K_2Cr_2O_7$). Ions in solution were shown by their chemical formula, and the different numbers of ions for different concentrations implied students' understanding of the particulate nature of matter. Students exhibiting this model in their drawing also included the idea of "dissociated ions" in their verbal descriptions of the dissolution process:

> Interviewer: What does it mean to you when something dissolves ... what do you picture occurring?
>
> Heather: The substance just like breaks down into ions, I guess. Um.. Like if you have a sodium chloride solution. And like you start out with a solid it just bounds and breaks till the ions are just floating in water.
>
> [He S/P: P1, L45-49; P2, L50-53]

Students who employed different models exhibited different degrees of understanding of solution chemistry. Generally speaking, students in the third Symbolic Ionic Model category displayed better comprehension of solution chemistry than the others. Three out of nine students – *Heather, Kevin, Shuan* – who employed the Symbolic Ionic Model throughout the interview showed evidences of better understanding of solubility and saturation. For example, one student who employed a Symbolic Ionic Model, *Shaun*, went so far as to represent the correct ratio of cations and anions in his drawing, in addition to clearly expressing the importance of the ionic ratio in the solution.

> Interviewer: What could you draw to represent your thinking about what's in each test tube?
>
> Shaun: I would draw it ... first of all, there's water in the whole thing. Inside the water there'd be, the test tube that's less concentrated, K^+ ... And then there would be like two of those. Two K's to every Cr_2O_7 of a solid, I think, or the other way around. No, it's this way. And then they are just scattered in a random motion. But in this one there'd be ... they'd look the same, only there'd be a lot more. And there'd be twice as many potassium as dichromate.
>
> [Sh S/P: P3, L129-143]

2. Students' Conceptual Understanding

1) Multiple Meanings of the Particulate Model

Student comments from those who employed the Particulate Model indicated two different conceptions of the particulate nature of the solution. While students such as *Monica* and *James* related that the circles they drew represented *molecules* of solute substances, other students indicated that these were *ions* in the test tube. Students who stated that the particles were ions, however, did not seem to have sufficient understanding to indicate accurate cations and anions. This partial understanding led them to identify ions that were inaccurate for Phenomena 1 (e.g., *Dagny*), or they were uncertain of the ions (e.g., *Rachel*). *Dagny* explained a solution as a mixture and result of "splitting up into their[solute's] different anions and cations". In addition, she stated that polarity of water was responsible for splitting up into ions. Even though she had an idea of 'breaking up ions' in a solution, she could not represent her ideas when she actually encountered phenomena which was different concentrated potassium dichromate solutions; such as which ion would be cations and which one would be anions. She illustrated K^+, CrO^-, Cr^-, and O^- ions in her drawings. She was uncertain about how to present her ideas by drawing. On the other hand, *Rachel* was able to explain solubility for molecular structure due to polarity of water. When she was asked to draw potassium dichromate solutions, she illustrated different numbers of dots for solutions with different concentrations. Then she explained that those dots represent ions that dissolved in the water.

Interestingly, when working with specific chemical solutions such as sodium chloride, sodium nitrate, and potassium nitrate which were simpler and more familiar substance in Phenomena 3, these students could represent specific ionic symbols instead of indistinct circles. It could be hypothesized from this finding that the use of the Particulate Model might indicate an intermediate developmental stage of student comprehension. As seen in Table 1, all students but *James* employed the Symbolic Ionic Model by Phenomenon 3. Even the students who showed the Undifferentiated Symbolic Model in Phenomena 1 & 2, indicated cations and anions in Phenomenon 3.

The occurrence of different conceptions of matter with drawings that look the same illustrates the importance of combining verbal descriptions with graphical representations in this kind of assessment. One representational system may not suffice to accurately indicate students' level of understanding.

2) Drawings Can Reveal Better Student Understanding Than Verbal Description Alone.

As discussed above, graphical representations of phenomena without verbal description or verbal descriptions alone can lead to misinterpretations of students' understanding. Nonetheless, graphical representations along with verbal descriptions helped us to assess student understanding more comprehensively most of the time. Therefore it can be argued that graphical representations can reveal students' actual understanding in ways that verbal descriptions alone cannot.

There were discrepancies between students' verbal explanations and their drawings in some cases. Although students could discuss molecular-level knowledge using chemical terms, they could not necessarily represent their ideas graphically. This observation is crucial because recall of text-based information may mask a lack of comprehension of underlying fundamental concepts. Some students were able to verbally state the phenomena using chemistry languages found in the textbook. However, their graphical representation did not show their proper understanding of the phenomena as they described.

For example, both *James* and *Kevin* mentioned "dissociation" or "breaking up" in their response to general questions regarding solutions and dissolution, but neither of their verbal responses included the notion of "ions". Their drawings (which showed K^+ cations and $Cr_2O_7^-$ anions), however, revealed a large difference in their perception. *James* began by providing the following information about solutions:

> Interviewer: How would you define being dissolved?
> James: Either partially or completely molecules dissociated into the solution. I don't know whether they break apart or what they ... I don't know how to explain it ... something is dissolved, it means that molecules dissociate into solution and I don't know after that.
> [Ja S/P: P2, L74-86]

> Interviewer: Why would any substance be necessarily more soluble in water compared to another substance that is not soluble?
> James: Well, I would have to say that I don't know, I say that the bond strengths of the ones found toward left to the periodic table are weaker and they can be broken easier and dissociated into a solution.
> [Ja S/P: P3, L103-109]

The concepts of "molecules dissociated into", "bond strengths", and "be broken" in the above statements might indicate *James'* understanding of dissociated "ions" as the result of dissolution. Although *James* did not explicitly state "ions" in his explanations, he was able to describe the processes associated with concepts of ions. However, *James* consistently described the circles in his drawings as *molecules* instead of ions. He did not depict separate cations($^+$) nor anions($^-$); rather he drew combined, not-dissociated circles representing molecules. This indicated that his notion of "dissociation" is not the same as a chemist's.

In contrast, *Kevin* was not able to verbalize his awareness well. He described dissolution as "... breaking up little by little. [The solute] would be like breaking off and then dispersing itself and not maintaining its solid form, but going into liquid [Ke S/P: P1, L21-22; L30-33]." His conception of dissolution became more obvious when he was asked to draw it; he then clearly indicated ions such as K^+ and $Cr_2O_7^-$ in each solution. *Kevin's* drawing, a Symbolic Ionic Model, revealed more of his understanding of dissociated ions than he had been able to indicate verbally. Therefore, analyses of graphical representations along with verbal descriptions helped us to analyze students' conceptual knowledge more thoroughly.

3) Changes in Models

As mentioned earlier, the range of students' representations varied by phenomena as well as by individual. The students' representations were consequently not static, but evolved throughout the interview.

Table 1 shows the categories of student molecular -level representations of solutions after differentiating students with Particulate Models into two different groups. All but two participants − *James* and *Shaun* − employed multiple models. In general, students tended to move to the Symbolic Ionic Model from Phenomenon 1 to Phenomenon 3. Three main themes were identified to characterize these changes.

Repeated opportunities provided time to develop ideas. Visualization of chemistry concepts appeared to be a new task for most of the students in our study. This study was conducted in the beginning of an introductory chemistry course, where many of course participants were freshmen taking this course as their one of the first university courses. While they hesitated at the beginning of the interview when asked to draw their ideas, they became familiar with the task and demonstrated more confidence performing it after they were asked repeatedly.

Laura's responses best illustrate this. Initially, she could only provide verbal descriptions of dissolution and had difficulty in representing her ideas graphically in response to the first phenomenon (see Fig. 3). The interview structure provided multiple opportunities for *Laura* to draw her ideas, which in turn gave her more time and experience to develop response strategies. During the interview, an interviewer continuously encouraged interviewees to freely express their ideas in drawings as well as in their verbal descriptions. The interviewer tried to make the interview situation safe to express ideas rather than press students to provide the right answers. The interviewer repeated the same question stems (e.g., *what do you picture occurring?*) to probe students' understanding in drawings. By the second phenomenon, *Laura* was able to utilize a Symbolic Ionic Model to depict her conception of "dissociated ions". Fig. 3b shows her initial and final graphical representations.

Additional phenomena (i.e., adding energy) triggered ideas. The property "heat" was introduced in the second part of Phenomenon 2, which concerned factors that influence solubility, and students observed that more potassium nitrate dissolved after heating. Students were also given an equation[4] as an aid and asked to explain why more potassium nitrate was dissolved after heating. Specific comments from two students, *Lee* and *Monica*, indicated that the introduction of the energy concept prompted them to

Table 1

Range of Students' Graphical Representations

	Phenomenon 1: *Concentration*	Phenomenon 2: *Solubility*	Phenomenon 3: *Chemical Reaction & Precipitation*
Undifferentiated Symbolic Model	Lee Laura	Lee	
Particulate Molecular Model	James Monica	James Monica	James
Particulate Ionic Model	Dagny Rachel	Dagny	
Symbolic Ionic Model	Heather Kevin Shaun	Heather Kevin Shaun Laura Rachel	Heather Kevin Shaun Laura Rachel Lee Monica Dagny

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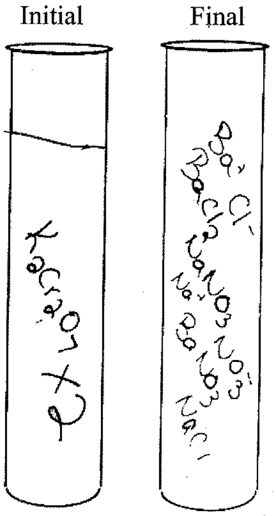
[4] $\triangle + KNO_3\,(aq) \rightleftarrows K^+ + NO_3^-(aq)$ ($\triangle$ means adding heat energy)

Interviewer: What do you picture happening when that salt dissolves into water?
Laura: Um, probably that the ions of each break up, and then combine with each other like kind of go together.
Interviewer: Could you draw something to show what you mean by that?
Laura: I don't know, but um, I don't know what to draw.
[La. S/P: P1, L46-52]

(a) Verbal Description in Phenomenon 1



(b) Initial and Final Graphical Representations

Fig. 3 *Laura's Verbal Description vs. Graphical Representation*

think about ions. They were able to incorporate the concept of "dissociation" in their description. For example, after heat was introduced as a factor in Phenomenon 2, *Lee* seemed to incorporate the idea of ions into her drawing and employed a Symbolic Ionic Model in her drawings concerning Phenomenon 3. The concept of ions were triggered by the introduction of heat in Phenomenon 2 and she was able to carried the concept throughout the interview. In Phenomenon 3, even different chemicals were presented, she was able to apply the concept of ions in this new phenomenon. *Monica* also related heat to dissociation. This is demonstrated in the following interview excerpt, which took place prior to heating the solution in Phenomenon 2.

Interviewer: What do you think is going to happen [after heating these solutions]?
Monica: They will dissolve ... Because you are heating it.
Interviewer: What is it about heating that might make them dissolve?
Monica: Probably because crystals break down and dissociate into ions which are made from compounds.
[Mo S/P: P5, L244-251]

In each student's case, the use of a Symbolic Ionic Model was limited to this one situation where heat was introduced in Phenomenon 2. This observation might indicate that their conception of ionic processes was not fully developed. Nevertheless, their use of it in the interview revealed their potential to develop adequate knowledge in the future.

Requirement of symbolic representation triggered ideas. Students were asked to write an equation describing the reactions in addition to drawing pictures for the third phenomenon. The nature of the task appeared to encourage them to employ Symbolic Ionic Models to depict what occurred. Their understanding, however, seemed to be varied. Most students depicted ions in their drawings for Phenomenon 3; yet, they did not necessarily employ them comparably in the chemical equations that they were asked to write. Some students put symbols such as (s) or (aq) after the molecular formula to indicate its solid or liquid state in the equation instead of indicating molecules or ions (cations or anions) as in their drawings. Furthermore, most students did not accurately balance their equations and usually failed to represent correct ratios of ions in their drawings as well. This imbalance between the symbolic representations of molecular and macroscopic levels is instructive concerning gaps and insufficient development of student comprehension.

Nevertheless, compared to their drawings, participants in this study generally seemed more comfortable composing equations, and several students constructed an accurate equation illustrating the chemical reaction although they were unable to depict the phenomenon graphically. Research reporting that chemistry students are acquiring algorithmic skills in working with symbols gives the impression of proficiency in chemistry, but the reality may be that they often misunderstand the meaning of the symbols (Ault, 2001; Nurrenbern & Pickering, 1987; Yarroch, 1985). In other words, students are often able to construct the right equations, but this ability does not necessarily show their proper understanding of the concerning concepts.

Ⅳ. Conclusion and Implications for Further Research

Previous research indicated three levels of representation in understanding chemistry: sensory, atomic/molecular, and symbolic. This study focused on the assessment of students' molecular-level representations because this level of understanding is critical to integrating the other two levels of representation (Gabel, 1998). This study found gaps and a lack of development in university students' conceptions of solutions, even after several years of formal study in middle school and beyond. Their weak comprehension at the molecular level became more obvious when they were asked to represent their conceptions in drawings. Few students exhibited an expert level of understanding, and several common inaccuracies were observed. This indicated typical difficulties students have in understanding common phenomena at the molecular level.

The study findings demonstrate how eliciting graphical representations is relevant to assessing student conceptual understanding.

1. *Graphical representations can predict students' conceptual understanding:* In general, students who had poor conceptual understanding tended to employ the Undifferentiated Symbolic Model, whereas students who had proper understanding tended to use the Symbolic Ionic Model. In many cases, therefore, students' conceptual understanding was predictable from their graphical representations. For example, a student who did not understand the idea of ions were not able to represent ions in her/his drawings. On the other hand, only students who had a proper understanding of ions were able to depict ions in their drawings. Of course, some students who had a proper understanding were not able to represent their understanding in drawings due to several reasons such as their lack of experience with graphical representation. Therefore, the absence of ions in the drawing does not necessarily indicate the lack of their understanding. However, the presence of ions in the drawings can be an indication of proper understanding. In that sense, graphical representations can predict students' conceptual understanding.

2. *Graphical representations can reveal and detect students' alternative concepts more easily and clearly:* Students frequently hesitated to draw pictures when they had partial or ambiguous understanding. Their explanations most often tended to comprise recollections of short definitions from textbooks. As they were prompted to elaborate further and represent their knowledge graphically – which might differ from a textbook presentation (which did not necessarily provide the same phenomena as this interview dealt with) – they demonstrated comprehension different from that of chemists. When students did not possess adequate understanding, they could not represent their conceptions in other ways besides what was presented in textbooks or what they were told. Sometimes students' explanations sounded reasonable, but their drawings showed discrepancies between their verbal descriptions and the graphical representations or accentuated their alternative understanding. In these cases, the graphical representations helped to elucidate what the particular student actually understood about the phenomena as opposed to their ambiguous verbal descriptions when they could not elaborate concepts beyond a short statement.

Problem solving in solution chemistry requires qualitative and integrated understanding of a variety of concepts. In order for students to develop relevant proficiency and strategic skills, students need to be taught with this fact in mind. How students are assessed provides them the most prominent message about what needs to be learned; thus, we need more assessment tools to evaluate students' qualitative comprehension. Chemists understand chemistry by relating their observations of macroscopic phenomena to their image of molecular structures and processes, and by using symbols to communicate their ideas and understanding. This study recommends more attention to molecular-level comprehension in research and teaching regarding linkages between macroscopic- and molecular-level representations.

The topics that students are tested on in an examination is known to impact what they learn in the classroom. Shavelson *et al.* (1991) pointed out the important relationship between assessment and curriculum by stating that "[g]ood instructional activities can be translated into assessments; good assessments can be used as instructional activities." Accordingly, the assessments discussed in this study can be viewed as instructional activities as well. If representation at the molecular level becomes expected, the conceptual comprehension arising from related activities can improve students' abilities to solve problems in a more desirable manner not by using algorithmic means, but by understanding underlying concepts, integrating both macroscopic phenomena and molecular structures and processes, and communicating with symbols. This issue is essential to successfully motivating student learning in chemistry and should not be overlooked.

In addition, the recent development of educational technologies holds a great deal of promises in this area. Animations, simulations, 3-D images, and guided inquiry scaffoldings all can be used to promote students' better understanding of particulate nature of matter (e.g., Ardac & Akaygun, 2004; Williamson & Abraham, 1995); such as computer-based visualizing tools include *4M:Chem* (Kozma *et al.,* 1996), *Chemsense* (Schank & Kozma, 2002), *eChem* (Wu *et al.,* 2001), *Seeing Through Chemistry* (Jones & Berger, 1995), etc. There is a need for further research on to what extent these computer-based visualization tools support students to make connections between different representations, and between representations and underlying concepts (Wu & Shah, 2004).

Abilities to use representations to generate explanations allow students to fluently translate one representation into another and make connections between representations and concepts. As Kozma (2000) stated, "the use and understanding of a range of representation is not only a significant part of what chemists do − in a profound sense it is chemistry" (p. 15). This stressed the importance of understanding and utilizing representations in chemistry learning and practice.

As investigated in this paper, "drawing your understanding" exercises can be used as an alternative assessment tool (e.g., Dove *et al.,* 1999) to identify where students might have alternative concepts. Moreover, this can be further developed as an effective instructional strategy in teaching conceptual understanding and problem solving skills in chemistry classes. Such drawing-based instructions have been implemented in elementary schools (Edens & Potter, 2001) and secondary schools (Han *et al.,* 2006; Kang & Noh, 2006; Kang *et al.,* 2005; Noh *et al.,* 2003; Noh & Jeon, 1997), and the learning effects of those interventions were validated. The application of the drawing-based instruction at a university-level calls for further research and this study shows urgent needs of such an instruction for university students since they also lack ability to articulate molecular understanding via texts and graphical representations as for younger students.

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Appendix. Sample Interview Questions

Introduction

Let's begin by talking generally about solution, solubility and dissolution.

a. What does it mean to say something is a solution?
b. What does it mean to you to say that a substance is insoluble?
c. Do you have any ideas about why something dissolves and something doesn't?
d. When something dissolves, what do you picture occurring?

Phenomenon I: Solutions and Concentration

This is Potassium Dichromate. I basically just added some Potassium Dichromate to water in these two test tubes [put different amounts of Potassium Dichromate in the test tubes]

a. How do you think those solutions are different? And why do you think that? How might you depict that?
b. [put enough Potassium Dichromate in the third test tube until some precipitates are visible at the bottom] How would you say this third test rube differs from the other two? How would you depict that in that last one?

Phenomenon II: Solubility with Solid Solute

Part 1: Here we have several different compounds; Sodium Chloride, Sodium Nitrate, and Potassium Nitrate. And I took some of them and dissolved them in the same amount. In this case, it was 10 grams each compound and put it in 20 milliliters of water.

a. Describe what you see in the beakers.
b. How do you think that these solutions are different?
c. Do you think there's anything happening between the substance on the bottom and the solution?

Part 2: I'm going to put these beakers on the hot plate.

a. What do you think is going to happen, if anything?
b. How do you know when something is saturated?

Phenomenon III: Solubility and PrecipitationIntroduction

I have several substances here; Barium Chloride, Sodium Nitrate and Sodium Sulfate.

a. What do you think will happen when I add the Barium Chloride and the Sodium Nitrate together?
b. What do you think will happen when I add the Barium Chloride and the Sodium Sulfate together?
c. Do you think there is any interaction between the solid and the liquid?
d. I would be interested in you drawing an equation to represent what you think is occurring or will occur.