

General Chemistry Students' Understanding of Structure–Function Relationships

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Abstract: The goal of this study was to examine general chemistry students' understanding of the relationship between the structure of chemical compounds and the chemical/physical properties of these compounds. Case studies of three undergraduate engineering students enrolled in the second semester of a year-long general chemistry course were conducted using Lewis electron-dot structures as a model for chemical structure. Over the course of a series of five interviews, each student was asked to use Lewis dot structures as a basis for analyzing five problem sets corresponding to the following topics from the second-semester course: Lewis acid–base reactions, the solubility of gases in aqueous solution, acid-dissociation equilibria, chemical kinetics, and thermodynamics. The interview data suggested that the students' perceptions or representations of Lewis dot structures could be classified primarily as either verbal-linguistic or symbolic. The two students for whom these structures were most often verbal-linguistic representations exhibited a dependence on the external or visual features of dot structures. Their descriptions of the aforementioned chemical and physical phenomena tended to be static and inconsistent with scientific reality. The student for whom these structures were more likely to be symbolic representations exhibited more dynamic and interactive descriptions, which were more consistent with what one would expect from a practicing chemist. For this student, the dot structures were true symbols in the sense that they had meaning beyond their external, visual features.

Introduction

For practicing chemists, the chemical and physical properties of compounds are inexorably linked to the structures of the atoms and molecules they contain. Some doubt exists, however, as to whether novice learners in chemistry make these connections. A significant amount of work has been done on elementary and secondary students' conceptions of matter and their understanding of how chemical reactions occur [1–4], and Gabel and Bunce [5], de Vos and Verdonk [6], and Gabel [7] have noted the importance of probing students' understanding of matter and emphasizing conceptual understanding in science instruction.

Prior work has shown that young students construct meanings about matter and chemical processes that are often inconsistent with current scientific theory. There is reason to believe, however, that college-level students frequently demonstrate similar difficulties. In his work with graduate students, Bodner [8] noted that a small, but significant, fraction of these students seemed to hold misconceptions that had historically been associated with younger students [8]. Coll and Treagust [9] argued that senior-level university students and graduate students tended to use simple models of covalent bonding to explain properties of molecules in spite of their exposure to more sophisticated and more mathematically complex theories.

Not much is known, however, about the connections that high-school and college-level students make between chemical structure and function. Peterson, Treagust, and Garnett [10] have described specific misconceptions that high-school students constructed in reference to covalent bonding, and Cachapuz and Martins [11] and Boo [12] have studied

students' conceptions of chemical bonding with respect to reaction energetics.

To further elucidate students' understanding of the relationship between the structure and function of chemical compounds we studied students enrolled in a two-semester, college-level general chemistry course for science and engineering majors at Purdue University. Because concepts such as *structure* and *function* were likely to be too vague for novice chemistry students to discuss, Lewis electron-dot structures were used as the basis for probing students' understanding of structure–function relationships. The choice of Lewis electron-dot structures—hereafter referred to as *dot structures*—was also a pragmatic one as the students enrolled in the course from which volunteers were selected have had experience with dot structures from both their high-school chemistry classes and the first-semester of the general chemistry course from which participants were recruited. It is important to recognize that this study was not interested in whether the students being interviewed knew how to draw dot structures—there was abundant evidence in the interview data to suggest that they did. Our goal was a better understanding of what these structures meant to the students when they used them. The study was based on the following guiding research question: *How do general chemistry students use Lewis electron-dot structures to describe chemical and physical processes?* The key question was whether undergraduate students ascribed genuine chemical meaning to dot structures or whether they applied superficial, “letter, line, and dot” interpretations with little to no grounding in scientific reality.

1. Review of topics associated with the interview
2. Overview of the interview session
3. Presentation of the first problem
4. Analysis of students' response before dot structures are drawn
5. Drawing of dot structures
6. Analysis of student's response using the dot structures
7. Repeat steps 3-6 for remaining problems
8. Review accepted answers based on textbook and lecture information from the previous semester.

Figure 1. General outline of interview guides.

Method of Inquiry

The research question upon which this study was based could only be addressed using qualitative research methods [13–15]. Large-scale, statistical studies were not appropriate because it is impossible to design a reliable, quantitative instrument that adequately probes what dot structures mean to students who use them. Quantitative techniques are ideally suited for documenting the outcomes of students' thought processes, whereas qualitative techniques provide powerful and flexible platforms for describing and categorizing students' understanding. We, therefore, adopted the think-aloud protocol [16, 17] that is commonly used to capture the process by which students solve problems.

The three students who participated in this study were all engineering majors enrolled in the second semester of a college-level general chemistry course for students from science and engineering. The three students were all in their first year of the engineering program and they had all taken the same first-semester general chemistry course during which the topic of Lewis dot structures was discussed. Inasmuch as these three participants all came from the same engineering program, they had been exposed to similar if not identical courses during their first and second semesters. There was no evidence of differences in either age or ethnicity within the sample population and both age and ethnicities were representative of what one would expect for students in the first year of an engineering curriculum. It also should be noted that these were students who did relatively well in both the first and second semester general chemistry courses.

Each student was interviewed five times throughout the semester and each interview lasted approximately one hour. All interviews were conducted by the first author. The fifteen interviews that represent the raw data upon which the conclusions of this study are based were tape-recorded and then transcribed, verbatim, to yield approximately 450 pages of transcripts. The students' written work from each interview was also collected for use during the data analysis.

For the purposes of analysis, these data were treated as a set of three case studies. Two of the participants in this study were male ("Jim" and "John"), one was female ("Jane"). Pseudonyms were created for each participant to maximize confidentiality. Permission to carry out this research was obtained from the appropriate IRB committee before the call was issued for volunteers to take part in the study.

The interview sessions were designed to coincide with topics being covered at that point in the second-semester course to facilitate familiarity with basic concepts and

vocabulary. The topics covered included Lewis acids and bases, aqueous solubilities of common gases, acid strength and equilibrium, chemical kinetics, and thermodynamics (enthalpy, entropy, and free energy). Inasmuch as these topics were distributed from shortly after the beginning of the semester until virtually the end of semester, so were the interviews.

The topics covered in the interviews are not necessarily topics with which dot structures are normally associated. The research question, however, was designed to probe the meaning that students gave to dot structures rather than assessing the quality of the dot structures they produced. We, therefore, deliberately chose to interview students during the semester after the semester in which dot structures had been covered in lecture and assessed on homework, quizzes, and exams. Inasmuch as the three students came from the same two-semester sequence, they were exposed to the same discussion of dot structures, although differences in both depth of exposure and approach to teaching this topic might have occurred in their high-school courses. There was no evidence within the 15 interviews to suggest that any of these students had difficulty understanding the process by which dot structures were generated. There was evidence, however, of differences in the meaning these students attributed to these structures.

At the beginning of the first interview, procedures for drawing dot structures were reviewed with each student. The review was based on the discussion of the writing of dot structures in the textbook by Bodner and Pardue [18]. To ensure that the students followed the same sequence of problems and that every problem was attempted, each interview also began with a review of the basic vocabulary associated with each topic. This was done to establish a comfortable rapport with the participants and to reduce confusion during the interviews. The interview guides for each of the five interviews followed the general sequence shown in Figure 1. The interview guides for the sessions that focused on Lewis acids and bases and on aqueous solubilities of common gases are shown in Figures 2 and 3, respectively.

Transcripts and artifacts of written work generated during the problem-solving interviews were integrated to form condensed, chronological case records [13] for each student. Each case record was approximately 50 pages in length. Only those data relevant to the research question were included in the case records; idle conversation and discussions of textbook answers were omitted. In the next section, several excerpts from the interviews will be presented to provide the basis for the patterns and assertions presented in later sections.

Results

This section will examine the students' responses from two portions of the interviews. We will focus on the reaction between ammonia and water from the interviews based on the Lewis acid–base interview guide and on the relative solubilities of oxygen and methane from the interviews that examined the aqueous solubilities of gases that were conducted toward the beginning of the semester. Although these excerpts represent a small fraction of the total interview data, these examples are sufficient to illustrate patterns in how the three students interpreted and applied dot structures throughout the course of the interviews and the semester. Note, an "I" in the excerpts refers to interviewer prompts and comments and the "S" refers to students' responses.

1. Review of topics associated with the interview
 - Rules for drawing dot structures (valence electrons, octet rule).
 - Dot structures drawn for water, ammonia, borane, the ammonium ion, and carbon dioxide.
 - Definitions of Lewis acid (electron acceptor) and Lewis base (electron donor).
 - Reaction between borane and ammonia as an example of a Lewis acid-base reaction.
2. Overview of the interview session: Two goals for the students.
 - To describe four chemical equations on a molecular level.
 - To identify the Lewis acid and Lewis base in each equation.
3. Four-step analysis of one of the four following chemical equations:

$$\text{NH}_3 + \text{H}_2\text{O} \rightarrow \text{NH}_4^+ + \text{OH}^-$$

$$\text{HF} + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{F}^-$$

$$\text{H}_2\text{O} + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{OH}^-$$

$$\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{HCO}_3^- + \text{H}^+$$
 - Description of reaction without dot structures.
 - Drawing dot structures for reactants and products.
 - Description of reaction with dot structures.
 - Identification of Lewis acid and Lewis base.
4. Repeat previous, four-step process for remaining chemical equations.
5. Review of accepted, textbook answers.

Figure 2. Interview guide for Lewis acids and bases.

Sample Interview Data for John. *Lewis Acid-Base Reaction between Ammonia and Water.* During the review session, John used the presence or absence of nonbonding electrons to correctly identify borane (BH₃) as the Lewis acid and ammonia (NH₃) as the Lewis base. When he was asked to explain the reaction between ammonia and water, however, he was faced with a system in which both reactants had nonbonding electrons. John based his explanation on the negative and positive signs that were associated with the two products, the ammonium and hydroxide ions. After initially asserting that the negative sign on the OH⁻ ion connoted the *loss* of an electron, John concluded that the negative sign on the OH⁻ ion meant that water gained an electron. Ammonia, accordingly, lost an electron due to the positive sign on the ammonium ion:

I: Ummm ... OK. Let's take a look at this one. Ammonia reacts with water to give us NH₄⁺, plus OH⁻. OK.

S: Whew! OK, alright. Well, you can tell right away which one is the acid and which one is the base.

I: OK.

S: Just because you got NH...oh, oh yeah. OK, you look at the water.

I: Um-hmm.

S: Since you go from H₂O to OH⁻ you must lose...yeah, that's still got...yeah, that wouldn't matter. OK, 'cuz it would lose one of its hydrogens.

I: OK.

S: ...to ammonia. But it [water] also loses. It becomes an electron short because it...no it adds an electron. It [water] gains an electron. So that makes it an acid. And you know this [ammonia] is the base.

John was unsure how electrons were being donated and accepted in the reaction after the dot structures were drawn. He understood that a hydrogen ion was transferred from the water

1. Review of topics associated with the interview
 - Definitions of solubility and polarity.
 - Dot structure and polar properties of water.
 - Dipole interactions between water molecules.
 - "Like dissolves like" principle of solubility.
2. Overview of the interview session: Two goals for the students.
 - To compare the solubilities of pairs of gases based on chemical formulas.
 - To compare the solubilities of pairs of gases based on dot structures.
3. Three-step analysis to compare the solubilities of one of four pairs of gases:
 - O₂ versus CH₄
 - O₂ versus NH₃
 - CO₂ versus HCl
 - CO₂ versus CO
 - Comparison of solubilities based on chemical formulas.
 - Drawing dot structures of both gases.
 - Comparison of solubilities based on dot structures.
4. Repeat previous, three-step process for remaining pairs of gases.
5. Review of accepted, textbook answers.

Figure 3. Interview guide for aqueous solubilities of common gases.

to the ammonia, but he did not understand how the electrons played a role. In the following excerpt, John became confused after realizing that ammonia and the ammonium ion had the same number of valence electrons in their dot structures:

I: Where is the confusion arising?

S: Well, 'cuz this [ammonia and the ammonium ion] would have the same number of electrons.

I: OK.

S: 'Cuz like eight and eight basically. So I guess looking at that [the dot structures] it would be hard to see how it's...unless you compare it to the number of ... to the number of atoms that are in it. Like, I could still have the same number of electrons as I did there. And that [ammonia] has the same number of electrons in it as that [ammonium].

I: OK.

S: So, looking at it that way doesn't help me decide if that's an acid and that's a base.

I: OK, well if you had to describe how this reaction occurs, what would you say?

S: I'd say the hydrogen...

I: Um-hmm.

S: ...went from the water to the ammonia.

I: OK.

S: But didn't take...it must not have taken any of its electrons with it.

I: OK.

S: So it would be...it would be a hydrogen donor, not an electron.

I: OK, that makes sense. I see what you are saying. So do you think that the Lewis structures are really helping you here?

S: No! They're confusing me. Heh-heh. No, I'm confused.

Despite the confusion, John used the negative charge on the hydroxide ion as a basis for correctly identifying water as the Lewis acid. Ammonia, by default, was identified as the Lewis base.

Relative Aqueous Solubilities of Oxygen and Methane. Based on the chemical formulas alone, John suggested that oxygen was more soluble in water than methane, but he offered no explanation. John then drew the dot structures for each molecule and conjectured that methane was more soluble due to the hydrogen bonding that took place between water and methane's four hydrogen atoms:

S: Ummm, well now looking at it I guess it'd seem that this [methane] is more soluble because of the hydrogen, because it would have hydrogen bonding with oxygens in water.

I: OK.

S: Which would tend to make it more soluble I think. It [water] would want to dissolve it more 'cuz it'd be...it'd be able to...more of a bond to form.

John understood each of the principles from the review session and he identified both oxygen and methane as nonpolar molecules. In spite of this, he used the presence of hydrogen atoms in methane as an indicator of hydrogen bonding and, thus, incorrectly identified methane as the more soluble gas.

Sample Interview Data for Jane. *Lewis Acid-Base Reaction between Ammonia and Water.* Jane skipped the analysis using the chemical formulas and she immediately drew the dot structures for the reactants and products. In a similar fashion to John, Jane used the charges on the products in her explanations. She interpreted the positive charge on the ammonium ion to indicate that the neutral ammonia molecule had lost a single electron:

S: OK, this is ... those are lone [two nonbonding electrons on the nitrogen in ammonia]. So, but it's [ammonia] gaining an electron.

I: OK.

S: But it's not gaining any electrons. Because it's, oh it's a positive [the ammonium ion]. Yes it is. What about positive and...wait a minute. Positive is losing electrons.

I: OK, I mean these species...these Lewis structures are drawn correctly the way you have them.

S: Right. OK, 'cuz nitrogen has five [valence electrons].

I: OK.

S: That's one, two, three, four, five...(pause). I'm getting confused now.

I: Why? I'm not sure I see. Where are you getting confused?

S: NH_4^+ [the ammonium ion]...minus. OK, OK, I understand. OK, so this [ammonia] is losing an electron because it's gaining a hydrogen, but its [nitrogen] already has five, so it has to lose an electron...which it loses to that [water].

Jane concluded that the loss of an electron was accompanied by the gain of a hydrogen. I asked Jane to explain which electron from the ammonia molecule was lost and to where it was donated. She claimed that one of the nonbonding electrons from ammonia was donated to the water molecule. The electron donation was therefore coupled to a hydrogen transfer. This line of reasoning led to her correctly identifying ammonia as the base and water as the acid.

Relative Aqueous Solubilities of Oxygen and Methane. Based solely on the chemical formulas, Jane predicted that methane had the greater solubility due to the presence of hydrogen atoms. Like John, Jane believed that hydrogens indicated hydrogen bonding. After unsuccessfully grappling with a polarity argument, she turned her attention to the nonbonding electrons on oxygen. As the following passage indicated, Jane hypothesized that the nonbonding pairs caused oxygen to undergo a chemical reaction in water:

S: Ummm, I don't know. Maybe like the extra [nonbonding pairs] electrons. That's all I can think about.

I: OK.

S: Moving some of them, or...or taking on some others to make...just a molecule. Just...I don't know.

I: Alright, why don't you run with that one. If we throw this [oxygen] in here [with water], what kinds of things might happen? Like you said, electrons [from the oxygen] moving here or there.

S: OK.

I: Just take your best shot.

S: Oh, I have no idea. Uhhh...I don't know. Maybe somehow this is...separate and make two other. I don't know, is it gonna make...is it gonna dissolve? I don't know. Does that [to dissolve] mean that it just stays in there or does it form other things?

I: It could mean a number...I mean, what do you...how would you explain it?

S: I...I have no idea. I would say maybe the two separate [oxygen atoms]...and form other molecules. But that's...I'm sure that's wrong or that's...

In later problems, Jane explained that the number of nonbonding electrons was proportional to solubility. This explanation, however, contradicted polarity arguments, which she had previously used.

Sample Interview Data for Jim. *Lewis Acid-Base Reaction between Ammonia and Water.* After drawing the dot structures, Jim concluded that one hydrogen atom from the water bonded with the nonbonding pair of electrons on nitrogen in ammonia. He clearly indicated an interaction between ammonia and water in his written work. Jim used this description to correctly identify ammonia as the base and water as the acid:

S: OK, well I think that a hydrogen is taken or ripped off, or whatever, from the ammonia, NH_3 . Er, off the oxygen [in water] and put on the NH_3 .

I: OK.

S: And the NH four...uhhh...four plus [ammonium]...and then...the OH [hydroxide] is left with...(pause)...yeah and the OH is left with two, four, six, eight, eight electrons.

I: Um-hmm.

S: And the hydrogen from the H_2O was attached to the two lone pairs [electrons] on the NH_3 .

I: OK.

S: And that's what you get.

Relative Aqueous Solubilities of Oxygen and Methane. Jim correctly identified oxygen as more soluble than methane based on their chemical formulas, but he offered no explanation. After the dot structures were drawn, he described the possible interactions with water. He correctly identified both molecules as nonpolar and began, consequently, to struggle with the relative solubilities. Like Jane, he turned his

Table 1. Summary of Students' Responses

	Interview Topic	
	Lewis acid–base chemistry	Aqueous gas solubility
John	Charges on products used to correctly identify acid and base. Unclear about role of electrons in reaction.	Presence of hydrogen in methane assumed to lead to hydrogen bonding. Incorrectly identified methane as more soluble.
Jane	Charges on products used to correctly identify acid and base Positive charge attributed to loss of a single electron, but no mechanism given Loss of electron associated with gain of hydrogen	Presence of nonbonding electrons assumed to cause chemical reactions. Number of nonbonding electrons proportional to solubility, which led to correct identification of oxygen as more soluble.
Jim	Interaction between ammonia and water. Bond forming between nonbonding pair of ammonia and a hydrogen on water led to correct identification of acid and base.	Nonbonding electrons on oxygen only site for hydrogen bonding to water. Interaction between oxygen and water led to correct identification of oxygen as more soluble.

attention to the nonbonding electrons on oxygen as a possible rationale for greater solubility. He quickly discarded this notion and he settled for an explanation based on the fact that the nonbonding electrons on oxygen were the only available sites for hydrogen bonding with water. Evidence for this was shown in the following excerpt, which was supported by Jim's written work:

I: OK, what's gonna happen?

S: The bonds between the O₂ is going to...alright. I'll think of it the other way maybe.

I: OK, now just polish off that idea. Just to make sure I know what you're talking about there.

S: Well the bond...in the O...in the O₂...one of the oxygens might bond to the hydrogen on the H₂O because it has a couple of lone pairs and that's the only place I'd think I'd put it [interaction with water] because oxygen will...I...I don't think pair...with this lone pairs.

The students' responses to the two interview questions from which these excerpts were extracted are summarized in Table 1. Although these interview excerpts represent a small percentage of the data from this study, they provide examples of the general patterns that were repeated over and over again in the fifteen interviews. They therefore provide a basis for the generalized assertions described in the next section.

Patterns in The Data: Students' Internal Representations of Lewis Electron-Dot Structures

To a chemistry instructor, John and Jane's explanations for the two problems were unconventional, and perhaps entirely incorrect. Their explanations tended to emphasize static interpretations of molecular structure, where the simple presence of ionic charges, hydrogens, and nonbonding electrons dictated function. Although these explanations were not correct from an instructional viewpoint, they were sufficient for John and Jane to reach their final answers, which were often correct.

Jim demonstrated a more dynamic, interactive approach to molecular structure. He clearly indicated more abstract reasoning that was not dependent on the superficial aspects of the dot structures.

From the perspective of the problem-solving literature, these data indicated clear differences in how these students mentally

represented dot structures in describing chemical and physical processes. Medin and Ross [19] defined a mental representation as an "internal model linked to external objects and events so as to preserve functionally relevant information." Bodner and Domin [20] gave a similar definition when they noted: "The construction of a mental representation is an interpretation process where concepts are applied to specific situations of interest." The modifiers *internal* and *mental* within the above definitions remind us that the representations we are trying to interpret are cognitive phenomena. An internal or mental representation stands for, but doesn't fully depict, an item or event; it is the brain's attempt to encode experiences. Thus, a representation is very different from a photograph, which preserves all the information in the scene down to the resolving power of the film. *External* representations are physical manifestations of these cognitive phenomena and can include a sequence of words used to describe information that resides in the mind, a drawing or a list of information that captures certain elements of the mental representation, or an equation an individual writes that shapes the way information is processed while solving problems.

It was clear from the data collected in this study that, although the three students used the same external representations for chemical structures—Lewis dot structures—there were differences in their functional, internal representations. The role of representation in chemical problem solving is well documented [20–22]. For the purposes of this study, the work of Bowen [21] and Bowen and Bodner [22], which analyzed the problem-solving processes of graduate students in an advanced synthetic organic chemistry course, is particularly useful. That work provided examples of seven distinct representational systems: *verbal-linguistic*, *symbolic*, *methodological*, *principles-oriented*, *literary*, *laboratory-oriented*, and *economic*. Three of these representational systems played a particularly important role in the problem-solving behavior exhibited by the organic chemistry graduate students: verbal-linguistic (e.g., aldehyde versus ketone; acetone versus 2-propanone versus dimethyl ketone; Wolff-Kishner, Diels-Alder, Michael addition, etc.), symbolic (e.g., line structures, Newman or Fischer projections, etc.), and methodological (e.g., the fact that a Grignard reagent is prepared by reacting an alkyl halide with magnesium metal in diethyl ether). Relatively few examples were found where organic chemistry graduate students used representational

systems that were principles-oriented (kinetic versus thermodynamic control, for example), literary (referring to work that had been published in the chemical literature), laboratory-oriented (referring to the steps that would actually be used in the laboratory), or economic (considering cost in terms of time, effort, or money).

Two of these representational systems, *verbal-linguistic* and *symbolic*, play a particularly important role in explaining the results of the data collected in this study. The two students—John and Jane—for whom Lewis dot structures were repeatedly used as *verbal-linguistic* representations tended to handle these structures as collections of letters, lines, and dots that were not “symbols” because they didn’t symbolize anything that reflected physical reality [20]. These representations often led to solutions that had little or no relation to current scientific thought.

The fact that dot structures were often nothing more than verbal-linguistic representations allowed Jane in the Lewis acid–base interview to describe processes where electrons and hydrogen atoms “jumped” between reactants, for example, with no explanation of how or why this would occur. John’s emphasis on the mere presence of negative and positive signs on the products—OH⁻ and NH₄⁺—also demonstrated a dependence on the surface features of dot structures. John made simple, one-to-one associations between these negative and positive *signs* and the gain and loss of electrons without ever translating these signs into the idea of positive and negative *charges* on the particles these representations are meant to symbolize. Like Jane, John’s explanations had little, if any, chemical meaning.

For Jim, however, dot structures were much more of a *symbolic* representation. He ascribed meaning to dot structures that exceeded the information present in the external representations. His explanations were more dynamic, interactive, and scientifically valid. In the reaction between ammonia and water, for example, he described a reaction mechanism that included interaction between the reactants. Such explanations showed an independence of the surface features of dot structures.

It is important to recognize that all three students in this study exhibited evidence that dot structures could, at times, be symbolic representations. At various points in the interviews, some degree of understanding that went beyond the visual features of dot structures became vital to understanding certain problems. Explanations in which the students used nothing more than chemical formulas as the basis for their arguments, however, were less likely to involve symbolic representations. This suggests that dot structures may have the potential to foster deeper, more symbolic understandings of molecular structure when used appropriately.

Suggestions for Teaching

Verbal-linguistic and symbolic representations provide a useful dichotomy for analyzing how students interpret structure–function relationships and how instruction might be improved. When chemistry instructors use them, dot structures are true symbols because they carry meaning that goes far beyond their two-dimensional appearance on paper. There is reason to doubt, however, whether students always ascribe similar, symbolic meanings to these structures. Bodner and Domin [20] expressed this doubt in reference to students’

understanding of the chemical equations used to represent reactions students encounter in organic chemistry:

Students believe that when they write this equation in their notebooks it is a direct copy of what the instructor writes on the blackboard. An external observer, comparing the two, would agree that the students’ notes seem to be direct copies of what the instructor wrote. In spite of this agreement, there is a fundamental difference between what the instructor and some of the students write. The instructor writes symbols, which represent a physical reality. All too often, students write letters and numbers and lines, which have no physical meaning to them.

The results of this study are consistent with prior work [23–24] that has shown that students often construct meaning that facilitates explanation and the generation of correct answers, but that does not reflect physical reality. In general, these alternative explanations, conceptions, or representations result from the individual nature of learning and they should be accounted for in instruction [25]. Marais and Jordan [26] suggested that traditional chemistry instruction might rely too heavily on external representations to the detriment of conceptual understanding. The data from the research presented here are consistent with such statements. John and Jane’s primarily verbal-linguistic representations of dot structures did not reflect physical reality. In many cases, the students perceived dot structures as nothing more than “letters and dots and lines.” Such representations are certainly not the intended goal of instruction.

With respect to teaching structural aspects of matter in general chemistry, this research prompts several questions:

- What is the motivation for teaching dot structures in general chemistry?
- Is the motivation strictly based on teaching bonding or do we want to foster more dynamic and interactive perspectives of chemical and physical processes?
- Are students being asked to draw dot structures without applying them to chemical or physical phenomena?
- If so, are we unknowingly fostering verbal-linguistic representations?
- Could we present dot structures in a more dynamic manner in general chemistry to develop symbolic meaning?
- Could this approach to structure in general chemistry serve as a primer for organic chemistry where symbolic representations are essential?
- Are the examples of inappropriate use of Lewis dot structures that occurred in this study simply the result of the fact that these structures are seldom explicitly used in the weeks and months after they are taught in the typical general chemistry course?

Left on their own to understand the meaning of dot structures, it is clear that students may not construct representations that are chemically correct. Only by incorporating structure in a functional, symbolic way can we address these misunderstandings.

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