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Lost in Lewis Structures: An Investigation of Student Difficulties in Developing Representational Competence

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Many science, technology, engineering, and mathematics (STEM) students are required to take chemistry courses, even though the logic for this requirement is often opaque to them. A prime justification for such requirements is the assumption that chemistry is necessary for the development of a robust understanding of the relationship between molecular-level structure and the behavior of physical, chemical, and biological systems. The ability to predict the properties of a material from its molecular structure (and vice versa) is central to such an understanding. However, the links between molecular-level structure and properties are complex and require thoughtful study, practice, and skill. Without a robust understanding of these principles, students presented with the chemical structures of large biomolecules, for example, can only respond with surface-level learning and memorization.

For many, the first step toward understanding structure–property relationships is the ability to draw and manipulate the simple chemical structures known as Lewis structures.[1] These representations can convey a great deal of structural information and can be used to predict and explain a substance's physical and chemical properties. However, despite nearly four decades of literature describing "improved" ways of teaching Lewis structures *(1–20)*, the creation of valid representations remains an elusive objective for many chemistry students, which leads us to the question: Why do students have such trouble with this task? After all, the rules for drawing Lewis structures are included in almost all chemistry texts, and indeed one author states (*14*, p 456) that "if students follow a set of rules faithfully, the difficulties... [with student understanding] should not arise".

While the creation of Lewis structures is not an end in itself, it is a key component to understanding a wide range of chemical observations: flaws and ambiguities in students' ability to create correct structures will inevitably produce obstacles when they need to interpret and apply these structural representations. We believe that conventional approaches to introducing students to the skill of drawing a *meaningful* Lewis structure is in direct conflict with current understanding of how people actually learn, and likely to generate didaskalogenic (instruction-induced) confusions. What may appear to the expert to be a simple task is, in fact, inherently difficult, complex, counterintuitive, and all too often meaningless to many students.

Constructivism and Meaningful Learning

Until quite recently, many educators believed that learning was a passive process and subscribed to the Aristotelian notion expounded by the English philosopher John Locke, namely, that the learner is nothing more than a tabula rasa (clean slate), upon which the teacher can impress new information *(21)*. Such a simplistic model fails to explain the difficulties that students frequently experience in the educational environment, and indeed, ignores the central role of the learner in the learning process. In recent decades, more student-centered models of learning have emerged, the most prevalent of which is constructivism.

According to the constructivist model, knowledge is actively constructed by each learner *(22, 23)*. For this process to be meaningful, three key components must be present *(24–26)*. First, students must possess relevant prior knowledge upon which to anchor new knowledge. Second, this new knowledge must be perceived by the student as "relevant to other knowledge" *(26)*. Finally, the learner "must consciously and deliberately choose to relate new knowledge to knowledge the learner already knows in some nontrivial way" *(26)*. As part of this process, the learner must explicitly recognize and resolve real and apparent inconsistencies between their pre-existing state and the new knowledge that they are trying to integrate into a new synthetic state: that is, as they learn. In this context, the teacher assumes a Socratic role, prompting the learner to identify and resolve factual and conceptual lacunae and implicit assumptions and their implications. In cases where these conditions have not been satisfied, students may feel that rote learning is either necessary or sufficient, that is, the "new knowledge" need not be connected to or reconciled with their pre-existing cognitive structure. It is memorized but not understood, and more likely than not, quickly forgotten.

To develop a Lewis structure for anything except the simplest species, beginning students need nontrivial knowledge that they do not actually possess. For example: when given the formula C_2H_6O, students have a large number of choices for how to arrange the atoms (never mind the bonds and electrons). In fact, unless the students have previously drawn or seen a similar example, it is unlikely that they will be able to come up with the appropriate arrangement for even quite simple molecules such as CH_2O or $C_2H_4O_2$. The idea that many concepts in chemistry are not logically developed, but require a complex interplay between prior knowledge and previously worked examples has been likened by Taber *(27)* to a form of "bootstrapping" (p 125):

> In other words, although we may think of chemistry as being a logical subject, many chemical concepts can *not* be learnt in

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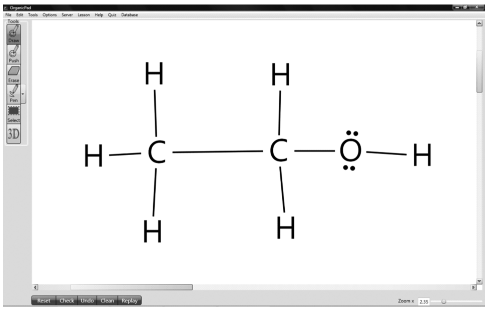

Figure 1. A screenshot from OrganicPad showing a user-created Lewis structure for ethanol.

an entirely logical manner, at least not in terms of clearly following deductively from previously accepted ideas and/or interpretation of empirical evidence.

We believe that current instructional practices make it almost impossible for most students to develop representational competence, that is, the skills that allow a person to use representations to understand chemical phenomena in terms of underlying physical entities and processes *(28)*. It appears that in the particular case of learning to draw Lewis structures, the fundamental requirements for meaningful learning are often omitted or obscured by the instructional process itself. To support this assertion, we present the results of a mixed-methods *(29, 30)* study of how students at all levels draw and use Lewis structures.

Methodology

The data presented in this paper were gathered as part of a larger project focused on the development and use of OrganicPad, a tablet PC-based structure drawing program[2] that provides individualized feedback for students as they construct Lewis structures. Although the development and features of this program are described in detail elsewhere *(31)*, we offer a brief summary of OrganicPad's features as they pertain to their use in the current study. Upon opening OrganicPad, users are presented with a blank workspace. Using the Draw tool, students can use the tablet PC stylus to write *Ink* strokes (atomic symbols, bonds, electron dots, and charges), which the built-in software converts into a more standardized format as depicted in the screenshot of the Lewis structure of ethanol in Figure 1. As students construct their representations, all user-made actions are recorded and stored in an online database for later replay. As such, OrganicPad allows researchers to see not only the students' final answers but also the individual steps that the students used to arrive at those answers.

All research participants were provided with information detailing their rights as human subjects; informed consent was obtained from all of the participants. This study was conducted with students and faculty of a research university located in the southeastern United States and utilized a mixed-methods approach *(29)*. While the participants were all affiliated with the same institution, they had a range of backgrounds. General chemistry students were taught by 10 different instructors using the same text, although the instructors were free to use their own teaching strategies. Students in organic chemistry had either taken general chemistry at the same institution, or had AP credit for general chemistry, or had transferred from another school. All graduate students had completed their undergraduate degrees at other institutions.

Quantitative Data Collection

Quantitative data collection began in the fall of 2008 when a convenience sampling of students *(30)* enrolled in Organic Chemistry I (N = 70) were asked to use OrganicPad to construct valid Lewis structures for nine compounds: CH_4O, CH_3COOH, CH_2O, HCN, CH_3OH, CH_6N^+, $C_2H_5O^-$, CH_5O^+, and $C_2H_3O_2^-$. These structures were chosen because they represent a range of tasks for students, including how to deal with different representations of the same compound (CH_4O and CH_3OH), double and triple bonds, and ions. Each submitted structure was analyzed for correctness and the mistakes made were characterized and tallied. In addition, the average success rate for each structure was determined.

Qualitative Data Collection

Participants in this phase of the study included 21 students (three general chemistry students, seven organic chemistry students, two juniors, three seniors, and six graduate students) and six faculty members. During interviews conducted in the spring of 2009, these participants were asked to draw Lewis structures for five compounds (NH_2^-, NO, CH_4S, C_2H_6O, and C_3H_7NO), and to explain the thought processes they used in doing so *(32)*. Participants were also asked a series of questions about their views of what Lewis structures were, what essential features they contained, and what information could be gleaned from such representations. A larger sampling of general chemistry students (N = 32) and organic chemistry students (N = 134), as well as four additional graduate students, was asked the same questions about their views on the use and functionality of Lewis structures using an online data collection program, Ed's Tools[3] *(33)*. The interviews were recorded using a digital voice recorder and transcribed. After each interview, the transcriptions were examined for emergent themes or trends *(34, 35)*. Subsequent interviews were modified on the basis of these emerging themes so that we might better probe student understanding of how and why they draw Lewis structures. Accordingly, the findings were fundamentally grounded in the data and continually refined as more data were collected.

Results and Discussion

OrganicPad and its tracking capabilities were used to monitor how students drew a range of simple organic structures. It should be noted that most organic chemistry faculty assume that students can draw simple structures and spend little time on this activity. In total, 527 Lewis structures were submitted on OrganicPad by organic chemistry students during the fall of 2008. A number of revealing trends emerged that were later echoed in the interviews; most importantly, many of the students (at all levels) as well as a few of the faculty members, were more than a little confused about how to construct valid Lewis structures.

As the number of atoms in the structure increased from six to seven and above (a change that corresponds to species with more than one carbon), the percent of students constructing correct representations fell significantly from around 80% (one carbon atom) to around 30% (two or more carbon atoms). While

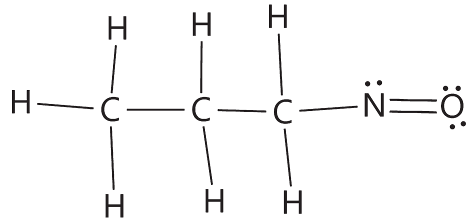

Figure 2. The Lewis structure for C_3H_7NO drawn by Ana Lucia and Jack.

it may not be surprising that increased molecular complexity makes the task more difficult for students, the fact that this difficulty becomes apparent in the transition from a one- to two-carbon species is quite startling and does not appear to have been previously reported in the literature. Furthermore, even for a one-carbon compound, students had difficulty if the formula was presented to them without structural cues. Around 60% of students drew a correct structure for CH_4O, a significantly lower percentage than those who could produce the same required structure for CH_3OH (>90%). That is, even for a relatively simple molecule like methanol, the number of organic chemistry students who could produce a correct representation was highly dependent on the way the formula was presented to them, suggesting that they were relying on memorized cues rather than an understanding of the rules involved.

These difficulties were also apparent in the student interviews. Many students expressed frustration at not being able to divine what the correct attachment of atoms should be. Students often coped with these difficulties by deriving rules from previous experience or remembering similar examples they had seen in class or their textbook. Jack,[4] an organic chemistry student, used his own rule to create the structural depiction of C_3H_7NO shown in Figure 2: "I always feel like the most common way would just be in one chain with all the main atoms in one row... just write it all out."

One of the more common ideas used by students was the notion that the most stable Lewis structures were those that were balanced or symmetrical (as depicted in the structures created by Jack and Ben, respectively, in Figure 3). Although it is true that symmetry plays an important role in many areas of chemistry *(36)*, it is unlikely that these students were explicitly taught this rule.

The Lewis structure of dimethyl ether that Jack created for C_2H_6O was correct; however, he did not feel comfortable with the other Lewis structure he generated for C_2H_6O, that is, ethanol, because it was not symmetrical and "[S]ymmetry always seems to lead to the right answer with chemistry." In trying to create a Lewis structure for CH_4S, Ben, a general chemistry student, had initially drawn a valid representation, but decided to change it because he felt uneasy about the carbon atom being bonded to three hydrogens while the sulfur was only bonded to one. Because of his need for "balance", he ultimately decided to change his answer to the incorrect structure shown in Figure 3.

Rules and Their Meaning

As a response to the necessity for "bootstrapping", educators have developed any number of rules and arcane procedures to "help" students become proficient at specific tasks. Unfortunately, these often abstract rules tend to conflict with the first and second requirements for meaningful learning: that is, what the learner is doing should be relevant to other knowledge and can be connected to concepts they already understand. Many of the schemes for drawing Lewis structures involve sets of rules that, while they may have some underlying rationale, are for all intents and purposes quite mysterious to the student, particularly because students must cope with numerous exceptions, again without meaningful criteria for deciding when they apply. For example, "the rules" state that the least electronegative element should be the central atom, but except in the case of simple, inorganic molecules, most compounds do not have one "central atom". While an experienced chemist might be able to explain the rationale behind these instructions, they are presented to students without connection to concepts that students can understand. That is, students are often placed in a "catch-22" position: they cannot actually perform a task until they already know how to do it.

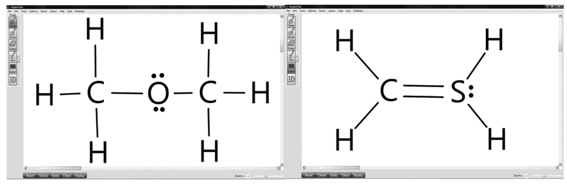

Figure 3. Examples of symmetrical Lewis structures constructed by Jack and Ben.

Oxygen and Nitrogen and the "Octet Rule"

Analysis of the OrganicPad data showed that organic chemistry students were twice as likely to show a nitrogen or oxygen atom as being electron-deficient or possessing an expanded octet, in comparison to carbon. Many of these same students were also unsure how to account for the positive or negative charges in their structures. Instead of adding or subtracting electrons from the overall tally, students waited until they generated a structure and then added or removed an electron from that structure, ultimately generating a radical.

Figure 4 depicts representations that contain more than eight electrons around a nitrogen or oxygen atom. While these results may not seem surprising to those who teach Lewis structures to students in introductory chemistry courses, it should be noted that the representations shown in Figure 4 were constructed by a general chemistry student, an organic chemistry student, and two faculty members.

Other students had a different problem; they invoked the octet rule in situations in which it was not relevant. Much like participants in other studies *(37−40)*, the informants in our work frequently relied upon anthropomorphic explanations when trying to construct their Lewis structures; in other words, atoms "wanted" or "needed" a certain number of electrons to make them "happy" or "stable" *whether the appropriate number of valence electrons were available or not*. When asked how she determined the number of electrons to portray in a structure, Claire, another organic chemistry student, explained that she continued to add electrons until "the octet [of each atom] is full". Because of this overwhelming urge to show atoms with full octets and a belief that electrons could be added until this was achieved, Claire and six other student participants (out of 16) drew Lewis structures for NO that depicted 12 electrons instead of the 11 actually available.

Student Perceptions of the Purpose of Lewis Structures

Students enrolled in general chemistry, organic chemistry, and chemistry graduate students were asked (both using Ed's Tools virtually and in face-to-face interviews) what kinds of information could be obtained from Lewis structures. Table 1 shows the percentage of students' Ed's Tools responses indicating the kinds of information that can be derived from a Lewis structure. Because we had a limited number of graduate student responses, we include both the number who were interviewed ($N = 6$) and answered questions on Ed's Tools ($N = 4$).

While all students indicated that some structural information could be obtained from Lewis structures (after all they are called Lewis *structures*), only about 30–40% of students indicated that Lewis structures could be used to predict molecular shape. Further, when interviewed, several students specifically indicated that Lewis structures could *not* be used in this fashion. When it came to chemical information, however, only about *half* the students indicated that Lewis structures have any utility.

Some students did understand the potential utility of Lewis structures. For example, Charlie (a graduate student) felt that they could provide insight into a molecule's reactivity:

> [Lewis structures] provide a really good picture of where the reactivity of the molecule would occur because if you explain reactivity based on valence electrons or lack of electrons (so negative charges, positive charges, lone pairs), you can get a really good idea of where the reactivity may take place...if there's going to be a reaction...and I think that's one of the more important aspects of it.

Other students indicated that Lewis structures could be used as a way to describe the intermolecular forces among molecules, which could ultimately serve to explain patterns in physical properties such as melting and boiling points. But these observations were in the minority and most students did not refer to any chemical information that could be inferred from a Lewis structure. Surprisingly, the percentage of organic chemistry students who connected Lewis structures with chemical information was generally smaller (31–56%) than the general chemistry students or graduate students. This is particularly troublesome because organic chemistry students are expected to use the very skills that are probed in these questions.

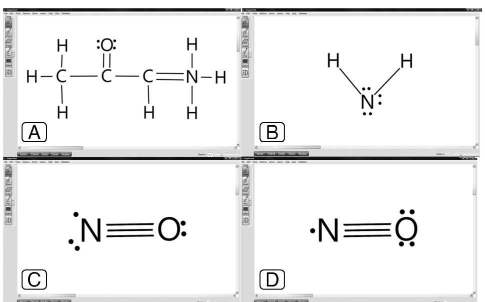

Figure 4. Lewis structures created by (A) a general chemistry student; (B) an organic chemistry student; and (C and D) two faculty members showing expanded octets on either a nitrogen or oxygen atom.

Implications for Teaching

We believe that our studies support our assertion that many students emerge from a range of chemistry courses with a fractured and muddled understanding of how to construct Lewis structures, and more tellingly, why they should learn to construct them in the first place. The process of learning to draw Lewis structures is cognitively complex; furthermore, it requires the recognition that Lewis structures are two-dimensional “shorthand” for three-dimensional information (the “real structure” of the molecule). Their construction often requires information that students may not possess and the application of a long sequence of obscure rules. The practical utility of learning how to draw Lewis structures (i.e., to allow students to predict and understand structure–property relationships) is lost in the process of learning to draw them. As far as many students are concerned, there are no compelling reasons that justify their efforts in mastering this skill. In response to our findings, we are currently developing and assessing new instructional design(s) that attempt to address the problems we have uncovered here.

We provide these suggestions based on our research presented here, in the hope that others will build on this research and attempt to provide a more meaningful instructional approach to this important topic. Our suggested approach is an attempt to integrate the knowledge that students need to construct a coherent framework for structure–property relationships. Students could be provided with experimental evidence for what molecules look like and their properties, and then allowed to construct explanations and tools (such as Lewis structures) to help them use those observations to make further predictions. We believe that such an approach is grounded in the framework of meaningful learning and constructivism, and will provide context and relevance to students that is lacking in much of our traditional instruction.

We suggest that covalent bonding and associated energy changes be introduced first, emphasizing that elements form bonds because the resulting system is more stable (not because elements “want octets”). This is a central concept that underlies much of chemistry, and might help alleviate the commonly held idea that bonds release energy when they break *(41)*. Next, physical and computer molecular models can be used to introduce the 3-D structures involved. We believe it is important for students to also develop an early understanding of the three-dimensional structure of molecules, beginning with simple molecules such as hydrocarbons, water, ammonia, and alcohols. Once students have the ability to construct models of small compounds (either physically or on the computer), they can be provided with data, including melting and boiling points, which students can use to investigate the relationship between 3D

Table 1. Comparison of Students' Responses[a] Regarding What Can Be Deduced from Lewis Structures

Information Interpretation by Students	General Chemistry, % (N = 32)	Organic Chemistry, % (N = 134)	Graduate Students, % (N = 10)
Students indicating that structural information can be obtained from Lewis structures	100	100	100
Students indicating that chemical information can be obtained	56	31	50

[a] These data were collected using Ed's Tools.

structure and the properties of these simple compounds. For example, students could observe the differences in melting and boiling points between linear and globular hydrocarbons of the same molecular formula, or differences between water and carbon dioxide, and better grasp the structure–property relationships. Compounds could be chosen to allow students to develop a range of concepts, but the overall goal is to have students construct an understanding of the connection between the 3D structure of a molecule, polarity, and properties. We believe it is crucial to emphasize this connection *before* students learn to draw Lewis structures, rather than using Lewis structures to illustrate structure–property relationships. This requires students to use the 2D structures to visualize 3D structures while concurrently learning about their properties, which is a much more cognitively demanding process. Lewis structures can then be introduced as a convenient way to represent 3D structures, rather than an end in themselves. That is, the only reason to require that students draw and interpret Lewis structures is so they can connect molecular structure and properties. Our research suggests that for many students, constructing the structure is the goal; they do not recognize that the Lewis structure is merely a tool or model to allow them to make sense of the chemistry they are learning.

To make the process of Lewis structure construction more manageable for beginning students, we suggest initial instruction be restricted to second-row elements and other common atoms. While the octet rule is a useful heuristic, it should be de-emphasized, because students confuse it with the reason bonds form. "Exceptions" should not be introduced until students have a strong grasp of the process. For introductory students, most expanded octets structures should be omitted (e.g., interhalogen ions and noble gas compounds, while fascinating for advanced students, make the task more difficult than necessary). Few (general chemistry) students progress further than organic; therefore, the emphasis on "central atoms" found in most rules is inappropriate. Students need practice in connecting chains of atoms: recall that making appropriate atom connections was a major problem, even for advanced students.

Finally, we believe that it is important for students to have continuous practice in drawing and using Lewis structures, in both formative and (if possible) summative assessments. Research has shown that students retain knowledge and skills better if those skills and knowledge are tested at multiple times during a semester. It is now possible for students to take courses in general (and organic) chemistry without ever constructing a response to an open-ended question, which cannot lead to the development of a robust understanding of Lewis structures and their uses.

Conclusions

Lewis structures can serve as a useful tool for consolidating chemical concepts, and their construction is an essential skill for both teachers and learners of the subject. This research has shown that students have numerous problems with the development and application of these ideas and that these problems do not abate as they progress through the curriculum. It is clear that the elements for meaningful learning are not present in most instructional designs for teaching Lewis structures. That is, most students use rules that are not connected with concepts they understand to perform a task that has no intrinsic meaning for them. It is not surprising, therefore, that students have trouble understanding and applying the "rules". It is crucial that we rethink how to best develop and reinforce these skills in a framework that allows students to learn in a meaningful way so that they can develop and appreciate the relationship between structure and function.

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Notes

1. We use "Lewis structures" to encompass structural representations that indicate atoms, bonds, lone pairs, unpaired electrons, and formal charges.
2. OrganicPad can be downloaded free of charge by visiting the OrganicPad home page at http://www.clemson.edu/organicpad (accessed Jun 2010).
3. Originally designed to collect student responses for the creation of concept inventories, Ed's Tools is an online system that allows researchers to ask open-ended questions of research participants. The answers can subsequently be coded using the native, java-based coding system *(33)*.
4. The names used throughout this report are pseudonyms. Further, to ensure that the participants' handwriting is not recognizable, the Lewis structures they drew for us on paper during the think-aloud interviews were recreated by the authors in OrganicPad.

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