Connecting Geometry and Chemistry: A Three-Step Approach to Three-Dimensional Thinking
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Supporting Information

ABSTRACT: A three-step active-learning approach is described to enhance the spatial abilities of general chemistry students with respect to three-dimensional molecular drawing and visualization. These activities are used in a medium-sized lecture hall with approximately 150 students in the first semester of the general chemistry course. The first activity involves using clay and sticks to help students visualize and overcome common misconceptions about geometric figures; the second activity involves connecting geometric figures with molecular shapes to foster an appreciation of the space that molecules fill; and the final activity is to introduce the more abstract valence shell electron pair repulsion theory using plastic, traditional molecular models to demonstrate how to represent molecules spatially on paper. The three activities can be done in three 55-min lectures with plenty of time for discussion.

KEYWORDS: First-Year Undergraduate/General, High School/Introductory Chemistry, Physical Chemistry, Collaborative/Cooperative Learning, Hands-On Learning/Manipulatives, Molecular Properties/Structure, Student-Centered Learning, VSEPR Theory

It has been shown that increased spatial capability leads to later success in chemistry courses as well as introductory physics and calculus.1 The simplicity of the valence shell electron pair repulsion theory (VSEPR theory) for predicting molecular shape has made it a popular approach to the introduction of the three-dimensional world of molecular chemistry.2−5 It has been our experience that students have a hard time making the connection between the two-dimensional drawings represented by Lewis dot structures and the three-dimensional structures used to predict molecular geometries. For example, a common question that is often asked when this material is introduced is, “Why is a structure made of five atoms called a tetrahedron, doesn’t tetra mean 4?” Although many activities have been published about teaching aides for the lecture hall,6−11 few of the models are actually made or manipulated by the students. The three lecture-based activities described here are completely built and investigated by the students. The three lecture-based activities described here are completely built and investigated by the students. The lecture-based activities described here are completely built and investigated by the students. The lecture-based activities described here are completely built and investigated by the students. The lecture-based activities described here are completely built and investigated by the students. The lecture-based activities described here are completely built and investigated by the students. The lecture-based activities described here are completely built and investigated by the students. The lecture-based activities described here are completely built and investigated by the students.

In these activities, students explore the different ways that atoms and lone pairs can arrange themselves around a central atom. For clarification, the authors use Lewis dot structure to indicate a two-dimensional structural drawing with no perspective or attention to angles. Electron pair geometries is used to describe the ideal geometry around a central atom that includes the lone pairs and the bonded atoms. The angles described therefore are ideal angles where all groups are treated as equals. Finally, molecular geometries consider the arrangements of just the atoms that are predicted by the electron pair geometries. Readers are encouraged to discuss with their students the benefits and limitations of this theory and, as a closing conversation, point out that lone pairs are considered larger than bonded atoms and therefore change the observed angles of some of the molecules used as examples. VSEPR is a theory that was developed to help explain what scientists observed.

■ ACTIVITY I: CLAY MODELS
The first activity in this series involves clay models and toothpicks (Figure 1). The kits consist of a resealable bag, toothpicks, and two different colored clays. The bags are handed out and shared among 2−3 students. The activity begins with two criteria: all balls representing atoms bonded to a central atom should be equidistant from each other and all angles between the balls should be equivalent.

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Students are then asked to build molecules using a central atom, toothpicks for bonds and spheres of different colored clay for the attached atoms. We begin building up from 2 groups or atoms connected to a central atom to 6 groups or atoms connected to a central atom. The linear model usually proceeds without much discussion; however, the two main geometries that are most commonly built for trigonal planar includes the correct structure and a T-shape. Discussion is encouraged to reinforce which one is the better answer with respect to the two criteria. It is the tetrahedron that actually presents the most challenge to the students. When models are held up for inspection, almost 50% of the groups will have a square plane (Figure 1). It takes considerable discussion before students realize that there are two different angels (90° and 180°) in the square plane. Once students have struggled with the tetrahedron, trigonal bipyramidal is more easily made, but the angles are still a problem for students because they violate the given criteria. Once the 4- and 5-vertex structures are mastered, the octahedron is then easily constructed, and by this time, students have enough facility with angles to predict 90° angles for the octahedron.

At the end of the activity, students are asked to break down their models, and hand in the kits in the same way the received them so that the next lecture section can use them. Start to finish this activity takes approximately 30 min of lecture time and the same kits have been used for several years with minimal replacement costs. The benefit of this activity is that students learn from their mistakes and construct their own understanding of three-dimensional molecules. Starting with traditional model kits that already “lock” the molecules into a set geometry does not give the students perspective on equivalent angles, limiting the learning potential for truly understanding the five basic electron pair geometries that form the basis for predicting molecular geometries.

**ACTIVITY II: TETRAHEDRAL KITES**

Because this activity is executed in a large auditorium with stadium seating and must be completed in 50 min, a kite kit (Figure 2) is provided to the students. Each kit contains enough materials for each group of students to make four individual tetrahedra (24 straws, four pieces of string, a stick of glue, four pieces of tissue paper, and a piece of wire for threading the string through the straws). Instructions for the building of the kite are omitted but a sample kite is made available, the point is to make the students think in three-dimensions to construct their own tetrahedra. The in-class handout is then used to direct the students to discover the connections between geometry and chemical structure. Using methane as an example, students build the molecule and investigate the relationships between the four-sided tetrahedral kite and the molecule.

This topic is generally reached in the sixth week of class and it is usually our first group activity. Groups of four to five students work particularly well for this activity. The group size is not overwhelming and each student has a clear role and assignment. In a class of 150 students, the instructor will have approximately 30 groups. To get them started, students are grouped (either by assignment or randomly; both have worked equally well) and instructed to elect a group leader. The group leader retrieves the kit and handouts and the other members of the group are instructed to each build their own kite. While the kite construction is progressing, the groups are working through the student handout simultaneously under the direction of the group leader. One question in particular, “Place your molecular model from handout part I inside the kite you just made, how are the two structures related?”, helps students synthesize the geometric connection (shown below in Figure 3A).

Once all four of the kites in the kit have been made, the students are instructed to create a large tetrahedron with their four kites (Figure 4). This larger tetrahedron is used later in the course to illustrate network solids, in particular, diamond.

**ACTIVITY III: CONNECTING THE ABSTRACT WITH THE CONCRETE**

In the third activity, the goal is to learn how to draw three-dimensional structures on paper in a way that represents molecules spatially. Students often struggle with drawing structures similar to those that instructors draw effortlessly on the blackboard. These beginning chemists often struggle with where to start, how to draw the lines, and what the wedges and dashes mean. Students begin by building the model with traditional plastic model kits. Starting with the central atom and the two planar structures, students draw what they see. Electron
pair geometries with more than three vertices require representation with wedges and dashes. Tetrahedral molecules are built and students are instructed to draw a dashed line on their paper and place the model straddling the line on the paper. This helps them visualize the plane of the board or paper and wedges and dashes are introduced to represent the three-dimensional model. Once students have mastered the five basic electron pair geometries in this way, the idea of molecular geometries is introduced. Balls are used to represent atoms and the vertex with a lone pair is left without a ball. Students are instructed to hold the model by the lone pairs to help them visualize the predicted shape. From here, the rest of the molecular geometries available for molecules with 2 through 6 vertices are introduced.

**RESULTS**

By the time these three activities are finished (approximately three 55-min lecture periods), students have a firm grasp on why a tetrahedral molecule has five atoms, how it relates to geometry and have begun to understand how to draw a representation for three-dimensional molecules. In addition, students have been introduced to molecular geometries with up to six vertices and have context for relative atomic distances and bond angles.

Student feedback on this activity has been positive. Comments include “I learn better through hands on activities, the kite activity was both educational and fun”. More than 70% of the students indicated on evaluations that this activity helped them remember the structure of the tetrahedron better. From the instructors’ standpoint, we were able to refer back to this experiment several times in the same semester. It is memorable and therefore a nice way of recalling the lecture and its message. Additionally, when network solids are discussed later in the semester, the picture that is already in students’ minds is that of the kite and the tetrahedron. This helps them understand common representations for diamond and other geological representations such as clays and gemstones (Figure 4).

**SUMMARY**

First-semester general chemistry is taught with an atom-first approach where the first third of the course focuses on atomic structure, orbitals, and valence bond theory and then followed by Lewis dot structures and VSEPR. This approach encourages more emphasis on structure, which will be a fundamental concept of many future chemistry and biology courses. Many general chemistry textbooks do not cover this material until much later, and consequently, it often is covered in lecture at the end of the semester. When this material is left to the last few weeks, it is rushed or often left out altogether assuming it will be covered in organic chemistry. The complexity of the material and the time it requires to master is countered by the importance of a solid foundation and understanding of three-dimensional structural work; therefore, more emphasis needs to be placed on molecular visualization. Molecular visualization is the basis for many upper-level courses in chemistry and beyond; the more often a student is exposed to structure building, the greater the ability to build upon the foundation and master higher-level thinking. These exercises, while simple, are memorable, hands-on, and give students a reference point to what for most may be the first time they see the molecular, geometric connection.

**ASSOCIATED CONTENT**

$^*$ Supporting Information

Student handout and kite building instructions. This material is available via the Internet at http://pubs.acs.org.

Figure 3. Constructing the tetrahedra and connecting them to tetrahedral molecules such as methane (A) methane model in the middle of the tetrahedron skeleton, (B) the finished kite, (C) the finished kite with the methane model. Photo credit to Ronnie J. Ortiz.

Figure 4. Four of the tetrahedra connected for a simplified diamond structure. Photo credit to Ronnie J. Ortiz.
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Notes
The authors declare no competing financial interest.

REFERENCES