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A Symmetry POGIL Activity for Inorganic Chemistry

Cynthia J. Luxford, Michael W. Crowder, and Stacey Lowery Bretz*

Department of Chemistry and Biochemistry, Miami University, Oxford, Ohio 45056, United States

Supporting Information

ABSTRACT: The goal of this project was to create an inquiry activity to teach symmetry elements and symmetry operations in an inorganic chemistry course. Many students experience difficulty when building and mentally manipulating three-dimensional mental models from two-dimensional images, causing difficulty when learning symmetry. Process-oriented, guided-inquiry learning (POGIL) was used to structure the activity using a learning cycle paradigm consistent with research on how students learn as described by Novak's human constructivism theory. The activity familiarized students with symmetry terms as students actively engaged in finding symmetry operations in a variety of molecules. The symmetry activity was classroom tested and student and POGIL expert feedback were used to improve the activity.

KEYWORDS: *Graduate Education/Research, Upper-Division Undergraduate, Inorganic Chemistry, Collaborative/Cooperative Learning, Hands-On Learning/Manipulatives, Inquiry-Based/Discovery Learning, Group Theory/Symmetry, Student-Centered Learning*

BACKGROUND

Symmetry is a fundamental topic in inorganic chemistry and provides an important foundation for other concepts, such as point-group notation, spectroscopy, and molecular orbital theory. Symmetry is included in the concepts required in the inorganic chemistry curriculum for ACS CPT approval.[1] Students need a firm understanding of symmetry in order to successfully understand many topics within inorganic chemistry, such as bonding and vibrational spectroscopy. However, many students struggle to learn symmetry due to the required visualization skills.[2,3] To successfully identify symmetry elements, symmetry operations, and to be able to apply these elements and operations to point groups, students need to be able to visualize molecules in three dimensions from drawings in two dimensions, and this skill is difficult for many students.[3,4] In addition, students need to be able to mentally manipulate molecules, for example, rotating molecules and finding mirror planes. The mental manipulation of molecules requires spatial ability skills with which students tend to struggle.[5−7] Therefore, we created an activity to enable students to learn symmetry in a more hands-on, interactive way.

One way to address struggles with visualization and spatial ability is for students to use three-dimensional models or computer simulations. A study by Copolo and Hounshell explored how high school students learn symmetry.[3] Students were placed in three types of classroom instruction for learning symmetry: traditional lecture, 3D models, and computer simulations. The researchers suggested that students who could physically manipulate 3D representations of molecules through either models or simulations might score higher on content tests than students who did not have models or simulations to physically work with. Dean Johnston at Otterbein University has created an extensive database that can be useful for helping students visualize symmetry operations.[8] Other options for aiding students in visualization include using 3D models.

THEORETICAL FRAMEWORKS

Most activities and resources currently available to teach symmetry are designed to check for student understanding rather than challenging the students to develop their own ideas.[9−14] We wanted to design a hands-on learning experience for students to explore symmetry operations and symmetry elements. We chose to create a process-oriented, guided-inquiry learning (POGIL) activity[15] as there are currently no publicly available POGIL activities for teaching symmetry operations. The role of the teacher in a POGIL classroom is different from the traditional classroom. Rather than lecture on new material to students, the teacher in a POGIL classroom facilitates groups of three or four students and guides them through the activity through the use of questions. As the teacher moves through the classroom, s/he actively listens to conversations that occur within the groups and decides whether to or how to intervene in the form of guiding questions. The students' responsibilities are to identify patterns and relationships in the models provided within the activity. Students must actively work to build new knowledge upon prior knowledge.

Novak's human constructivism theory posits that students learn through connecting prior knowledge to new knowledge.[16] Meaningful learning requires relevant prior knowledge. In a typical classroom, students will have different experiences, and therefore, also differing prior knowledge. To address this, POGIL activities provide models that contain information that all students can use to build new knowledge.[15] This provides students with a common experience that will enable them to interact and challenge one another as they learn. It is important to note that prior knowledge does not just refer to content; it also includes student knowledge of how to learn.

To help students learn how to build upon their prior knowledge, POGIL activities are structured using the three stages of the learning cycle.[17−19] Students begin learning

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through *exploration*. At this stage, they begin to connect prior knowledge to new knowledge. The prior knowledge is provided in the form of models. Models are key pieces of information such as a table or diagram that students can use to recognize patterns and relationships about the concept being learned. The second stage, *concept invention*, occurs when students actively work in groups to specifically articulate their understanding of the patterns and relationships they see in the model(s). The group work helps students develop correct concepts by allowing the students to challenge each idea brought up by the group. It is during group work that misconceptions can be discovered and addressed. The new concept is then *applied* through the use of exercise questions and additional readings. Exercise questions help both the teacher and the student gauge to what extent the student has learned the important concepts during the activity. The reinforcement of the concept causes students to realize both the limitations and additional applications of the concept.

■ ACTIVITY DESIGN

The activity was designed to be completed in two, 50-min periods. It consists of two models, critical thinking questions that allow students to develop new knowledge, and exercise questions to require students to apply their new knowledge to more traditional types of questions. (The complete activity and instructor's guide are available in the online Supporting Information.) In the first model, students explore the symmetry of ammonia (Figure 1). The students apply what they learned

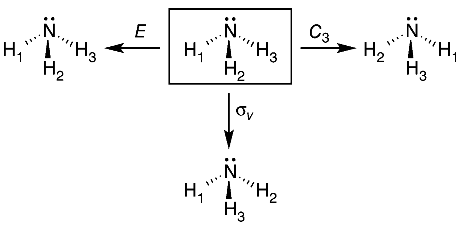

Figure 1. Model 1: ammonia.

in the first model to a second model, *trans*-dibromotetrachlorocobaltate (3−) (Figure 2), and then learn the additional symmetry operations.

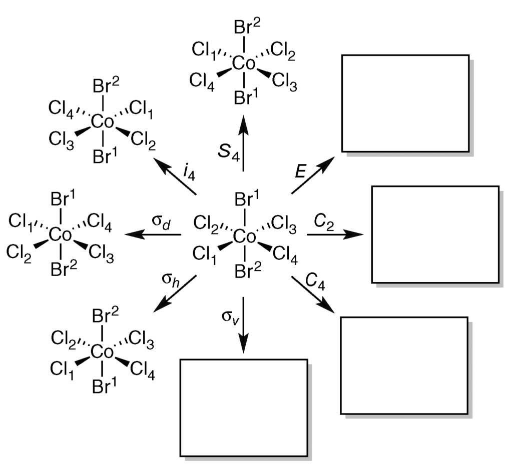

Figure 2. Model 2: *trans*-dibromotetrachlorocobaltate (3−).

Model 1 was designed to familiarize students with what is meant by a symmetry operation, leading the students to develop their own definition and understanding of the symmetry operations "E", "C_3", and "σ_v". The critical thinking questions expected students to make observations and then, based on those observations, create a working definition for each of the symmetry operations. Students tested the validity of their working definitions by exchanging one of the hydrogens for a chlorine atom, asking themselves whether "E", "C_3", and "σ_v" are still possible, and if so, drawing the possible arrangements. Students were then provided additional information about symmetry elements and symmetry operations; namely, that in order for a symmetry operation to be valid, the initial structure must look identical with regard to the placement of types of atoms after the symmetry operation was applied. Students were then asked to go back to NH_2Cl and check to see whether the arrangements were valid structures.

Model 2 provided the structure of *trans*-dibromotetrachlorocobaltate (3−) (Figure 2). Students were asked to draw structures in the boxes to indicate the results of the symmetry operations "E", "C_2", "C_4", and "σ_v". The critical thinking questions were designed to lead students toward creating working definitions for the different reflections, inversion, and improper rotations. In addition, the critical thinking questions in this section required students to reflect upon how they answered questions regarding the first model and to apply those same strategies to these new symmetry operations.

The exercise questions were designed to match possible questions the students might typically encounter in their textbooks and on exams. These questions asked students to apply what they learned in the activity.

■ IMPLEMENTATION

This activity was tested at Miami University in CHM 417/517 Advanced Inorganic Chemistry, a course designed for both graduate and undergraduate students. The class had 19 students enrolled: 5 undergraduate students and 14 graduate students. Typical topics in this course include valence bond theory, Lewis structures, symmetry, molecular orbital theory, acid−base chemistry, coordination chemistry, solid state chemistry, organometallic chemistry, and bioinorganic chemistry. Prior to this activity, none of the students had participated in any activities in which group work was required in the lecture course.

On the first day of the POGIL activity, the professor teaching the class handed the class over to the first author. Both the professor and the second author observed and interacted with the student groups throughout the activity. The students were permitted to arrange themselves into groups of four for the first class period. The students were instructed prior to attending class that they should not read ahead to the chapter on symmetry in their textbooks. Students were introduced to traditional POGIL roles during the first few minutes of the first class period, although we did not strictly enforce the roles in the groups. Student groups were provided with molecule kits and strongly encouraged to build molecules to help them visualize the symmetry elements and symmetry operations. All the groups of students used the kits as they worked through the activity on both days. Many students built the before and after molecules for each symmetry operation and then used the two models to discern the relationship between the two molecules. The activity was designed with the expectation that students would spend the first day working on Model 1. By the end of the first period, all groups had reached the last question of Model 1 and were asked to reflect in writing upon both their ability to work in groups and the focus and objectives of the activity. Groups that finished Model 1 were permitted to move on to Model 2.

The second period was intended for all groups to work on Model 2 and the exercise questions. Students were assigned to new groups for the second period by the first author. All groups started the second period with fresh copies of Model 2. At the end of the second period, the majority of the students had completed the questions about “i” and most students were beginning to answer questions about “S”. Students were assigned to read the sections of the textbook about symmetry operations and to answer the exercise questions as homework. Students were asked to return the exercise questions, along with the feedback survey.

■ INSTRUCTOR FEEDBACK

During the first period, it quickly became apparent that half of the students had some prior knowledge of symmetry while the other half had never encountered it before within their previous chemistry courses. This caused some groups to rely more heavily on the students who seemed confident in their knowledge of symmetry, sometimes to the point that the student or students with prior knowledge attempted to do the activity alone and have the rest of the group members simply copy down the answers. To address these group issues, students were placed into new groups for the second period. The intent was for students to work with new peers, thereby disrupting any patterns of over-reliance upon one person. Because all students had the same or similar knowledge from the first part of the activity, changing the groups increased student interactions. This was effective with regard to keeping more students actively engaged, although some students did not respond favorably to the new groups. Because of the students not knowing exactly what the other students in their new groups understood, the pace of the activity seemed to proceed more slowly in the second period than had been anticipated.

One unexpected aspect of prior knowledge arose in a group comprised entirely of graduate students concentrating in organic chemistry. They initially struggled with the concept of mirror planes. After the facilitators asked them several questions about reflection, it became apparent that the students were confused about the differences between the role of mirror planes as used to understand enantiomers in organic chemistry, versus reflection symmetry operations as typically encountered in inorganic chemistry. The students came to realize the important distinction that the mirror plane for inorganic symmetry reflection is within the molecule and the mirror plane for organic chemistry enantiomers is between two different molecules. This vignette offers a reminder that prior knowledge, while often thought to facilitate learning, can, in fact, hinder it in some circumstances. One strength of POGIL activities is that they allow students to explore new knowledge while working to build upon prior knowledge. Asking students to develop their understanding of symmetry in a classroom setting through this POGIL activity revealed a key aspect of their prior knowledge from organic chemistry that was interfering with their understanding of symmetry in inorganic chemistry. The opportunity for points of confusion about prior chemistry knowledge to emerge in a lecture setting are limited.

■ STUDENT AND EXPERT FEEDBACK

Students completed an anonymous survey at the end of the second period of the activity. Of the 11 surveys returned, five students indicated that they had previously studied symmetry. Six students reported that the question that they thought was most beneficial for their learning was the one in which they were asked to fill in the boxes at the beginning of Model 2. One student commented, “I like the second activity because everything just clicked for me. I could finally see three dimensionally without elaborate structures.” Students found creating definitions, the exercise questions, and working in groups to be the most challenging aspects of the symmetry POGIL activity. On the basis of student feedback, a few modifications were made to improve question clarity.

The revised activity was then scored against the seventh version of the Quality Indicator Rubric by two of the rubric’s creators.[20] The activity was subsequently modified to incorporate the feedback from the expert reviewers based on the rubric. Contrary to student feedback, the experts felt that group-created definitions were important for aiding students as they progress through the activity. The final version of the activity can be found in the online Supporting Information.

■ CONCLUSIONS

The primary goal of this project was to create a process-oriented, guided-inquiry symmetry activity that can be used to expose students to symmetry elements and symmetry operations, and to aid students in the visualization of the symmetry operations. The symmetry activity allowed students to explore symmetry elements and operations through student-centered learning rather than traditional lecture. The students were challenged to create definitions of the common symmetry terms; however, POGIL experts have reinforced the benefits of having students create their own definitions, rather than simply providing them with a standard definition. This activity enabled the facilitator to identify prior knowledge that interferes with the acquisition of new knowledge. Traditional lecture had not previously allowed these ideas to surface, nor addressed them. In addition, molecular model kits were included to support students in converting two-dimensional images to concrete, three-dimensional models.

Now that the symmetry activity has been created, faculty who teach inorganic chemistry are invited to use it to more closely study students’ learning of symmetry in their own classrooms across a wide variety of institutions with students who bring a diversity of prior knowledge to their study of symmetry. Future research studies could be designed to compare student learning of symmetry concepts using this POGIL activity against other learning modalities, such as lecture and computer visualizations.

■ ASSOCIATED CONTENT

Supporting Information

Notes for the instructor and guide for students. This material is available via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: bretzsl@muohio.edu.

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