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Designing, Teaching, and Evaluating a Unit on Symmetry and Crystallography in the High School Classroom

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Symmetry is a central element not only of chemistry, but also of physics, art, design, and architecture. Although typically not addressed explicitly until an upper-level inorganic chemistry course for chemistry majors, an intuitive understanding of symmetry is implied in the context of molecular structure and the VSEPR model in introductory chemistry, and in the study of chirality, stereoisomerism, and spectroscopy in organic chemistry courses. Despite the use of three-dimensional modeling software and ubiquitous modeling kits, students still have a difficult time visualizing a three-dimensional chemical world. McKay and Boone have argued that earlier development of the language and cognitive framework for symmetry may aid students in understanding the chemical concepts introduced in later courses *(1).* Although a great deal of work has been done to create educational materials on symmetry for college chemistry classrooms (e.g., refs *2–8*), the literature has much less work that explores this important issue in high school chemistry *(9–11).*

Both symmetry and crystals are naturally interesting to children; in fact, Friederich Froebel, the inventor of kindergarten, was trained as a crystallographer and believed that "the strongest start for young minds was training in the principles of point and translational symmetry" *(12).* Crystals are typically seen as more the realm of geologists than of chemists. However, an understanding of crystal growth, morphology, and analysis is essential to materials science, physics, and structural molecular biology. More than a dozen Nobel Prizes have been granted for work involving crystallography, including prizes in chemistry, physics, and physiology and medicine *(13).* These two topics, then, seem a reasonable starting point both for connecting high school chemistry students to the wider world, and introducing them to concepts generally reserved for higher-level courses.

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Project Goals

The primary goal of this work was to develop a series of lessons that could be used in the high school classroom to investigate crystals and symmetry. Such a unit was envisioned to be appropriate for any level of chemistry instruction from introductory high school chemistry to advanced placement. A secondary, yet important goal of this project was to facilitate outreach between the university science community and high school students and teachers. By having research-active graduate students, postdoctoral researchers, and undergraduates involved in lesson development and instruction, high school students and teachers are exposed to "scientists at work", while similarly, university students gain the increased insight into their own work by teaching it to others.

Symmetry and Crystallography for High School Students

Teaching and Research Setting

A two-week unit was developed and implemented in two high school chemistry classes, each with approximately 18 students. The unit development and instruction were collaborative efforts involving the high school chemistry teacher (Guerin), a chemistry education doctoral student (Grove), and a dozen members of the Zhou research group at Miami University. The unit was developed around two main themes: symmetry and crystallography. Each theme was introduced and developed over a series of three lessons, including demonstrations and hands-on activities. The unit ended by exploring the connections between both themes and culminated with a field trip to the Miami University science facilities. A brief description of each unit is provided below; a complete copy of the instructional materials used during the units is included in the online supplement.

Symmetry Thematic Unit

Students began their study of symmetry with the concepts of chirality and mirror symmetry through the examination of enantiomers. Cotton balls infused with *S*-(+)- and *R*-(−)-carvone (oil of caraway and oil of wintergreen, respectively) were distributed in vials to the students to demonstrate the physiological importance of stereoisomers *(14)*. Discussion continued about other enantiomeric molecules that may have been familiar to students, including common pharmaceuticals (methylphenidate, dextromethorphan, etc.), proteins, sugars, and DNA. Subsequently, students were shown models and animations of molecules in three dimensions, and the relationship between chirality and mirror symmetry was discussed. The second lesson further examined symmetry, including rotation, reflection, and inversion. A number of examples, illustrations, and animations of each were discussed. The third lesson, symmetry groups, instructed students in the classification of an object into basic point groups based on the symmetries present. Students were then asked to construct paper models demonstrating various point groups, including snowflakes, patterns inscribed in a circle, and tilings. Throughout the lessons, students were encouraged to find examples in the room around them and everyday objects at home that would represent various symmetries and point groups.

Crystallography Thematic Unit

The unit's second section—crystallography—was introduced by reviewing phases of matter (solid, liquid, gas), focusing on the solid phase, as well as the relationship between crystalline and amorphous solids. The concept of translational symmetry was also introduced as the fundamental definition of the crystalline phase. Students explored the wide variety of crystalline materials found in the world, from obvious minerals and gems to electronics, metallurgical products, and biology and medicine.

Each student grew his or her own high-quality crystals using a variety of methods, with appropriate safety precautions *(15)*. Students examined these crystals by unaided eye and under stereomicroscopes and were required to describe the morphology of the crystals they viewed using the symmetry terms learned previously. The class was then taken on a photographic tour of a single-crystal diffractometer facility, which included a demonstration using a grating and laser to illustrate the phenomenon of diffraction *(16)*. Wood blocks from a child's block set were used to explore the three simplest crystal systems (cubic, tetragonal, orthorhombic) and their characteristic symmetries.

Culminating Activity

The final activity of the unit was a six-hour field trip to Miami University's chemistry and geology facilities. Students toured the Limper Geology Museum, explored a variety of crystals and molecules using visualization software, and toured the X-ray diffraction facility. The tour compared the equipment in the X-ray diffraction facility to that in the previous photographic tour, and the safety equipment used to protect crystallographers was demonstrated. The research of the Zhou group in metal–organic frameworks as hydrogen-storage materials was discussed with the students. During this discussion, students were given 3-D glasses to view a crystallographic structure as it was solved in real time and were able to observe the presence of micropores in the material that are used for hydrogen storage.

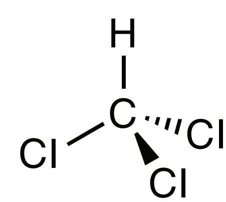
Impact on Student Learning

Prior to the instructional unit, students' knowledge of symmetry and crystallography was assessed with a pretest consisting of ten, two-tiered questions: five of these statements focused on symmetry, the other five on crystallography. Each two-tiered question consisted of a multiple-choice question and a paired follow-up requiring students to explain and elaborate upon their answer to the multiple-choice problem *(17, 18)*. These questions were written by the researchers and probed students' understanding of the important concepts taught throughout the two-week experience. An example of a symmetry-themed, two-tiered question is shown in Figure 1.

The assessment was administered again approximately three weeks after the conclusion of the unit. Students received one point for a correct answer on the multiple-choice section. On the elaboration and explanation section, students received two points for a correct answer, one point for a partially correct explanation, and no points for an incorrect explanation or for leaving it blank. A total score was calculated by adding the results of both sections together. Thus, the scores on the assessment instrument theoretically range from a score of zero to a maximum of 30 points.

Finally, a short questionnaire was given to the students at the unit's end to gather overall opinions of the unit and solicit feedback about both the strengths and weaknesses of the materials developed. The assessment instrument and opinion questionnaire are included in the online supplement. All research participants were provided with information regarding their rights as human subjects; informed assent and consent were obtained from all participants and their legal guardians, respectively.

4. Chloroform, $CHCl_3$, was once used in the United States for general anesthesia. Its 3-D structure is below.



Chloroform contains which of the following symmetry operations? (Select one.)

(A) Identity, C_3, point of inversion

(B) Identity, C_2, mirror plane

(C) Identity, C_3, mirror plane

(D) C_3, point of inversion, improper rotation

Using the space below, redraw the molecule and indicate all appropriate symmetry operations on it. Note that you may need to draw the molecule in more than one way to show all symmetry operations.

Figure 1. Example of a symmetry-themed, two-tiered question.

Results

Results from the pre- and posttests are included in Table 1. Statistical analyses were performed using Statistical Package for the Social Sciences (SPSS) Version 13 *(19).* Because the sample size was small, the distribution of each variable was tested for normality before any pre–post comparisons were performed. Histograms for the pre–post scores for each variable are included in Figure 2. The Kolmogorov–Smirnov normality test confirmed that the scores were not normally distributed; thus, pretest and posttest comparisons were performed using the nonparametric Wilcoxon signed-rank test. Values for Z and the associated significance levels are presented in Table 1.

As the data reported in Table 1 demonstrate, posttest scores showed a significant increase over the corresponding pretest scores, indicating that students learned and retained some knowledge about symmetry and crystallography even three weeks after the conclusion of the unit. To ascertain how well students' answers on the multiple-choice questions correlated with their answers on the elaboration–explanation portion of the assessment, Pearson's product-moment correlation coefficients were calculated for both the pre- and posttests. Initially, only a slight correlation ($r = 0.2$) existed between the total score of the multiple-choice questions and the total score of paired elaboration–explanation items, confirming initial speculation that most students were merely guessing when selecting a correct response on one of the multiple-choice questions. Conversely, the posttest correlation was large ($r = 0.7$); in other words, many students who were able to select correct responses on the posttest multiple-choice questions were also able to elaborate and explain their choices.

Discussion

Speaking about their experiences, most students felt that the hands-on activities and connections made between the academic and real world were the biggest strengths of the two-week unit:

> Seeing the different examples [of symmetry and X-ray crystallography] was my favorite part of the unit because then I saw how it applied to real life. I also liked the concept of making discoveries to benefit mankind because some issues like hydrogen powered cars are *very* important. [emphasis in the original]

Students also indicated that they enjoyed the field trip to Miami University to see and learn more about the cutting-edge instrumentation involved in studying symmetry and crystallography in the chemistry laboratory environment.

The unit and its implementation had weaknesses, as well. Despite efforts to make these sophisticated topics accessible to high school chemistry students, many of these students indicated that they still found aspects of the unit—particularly symmetry

Table 1. Comparison of Pretest and Posttest Scores by Question Topic

Test Version and Question Topic (*N*)	Mean Score	Standard Deviation	*Z* Value	Significance Level
Pretest—Symmetry (38)	1.37	1.24	-3.388	<0.001
Posttest—Symmetry (35)	3.17	2.24		
Pretest—Crystallography (38)	2.00	1.38	-3.227	0.001
Posttest—Crystallography (35)	3.57	2.05		
Pretest—Total (38)	3.37	1.99	-4.343	0.001
Posttest—Total (35)	6.74	2.75		

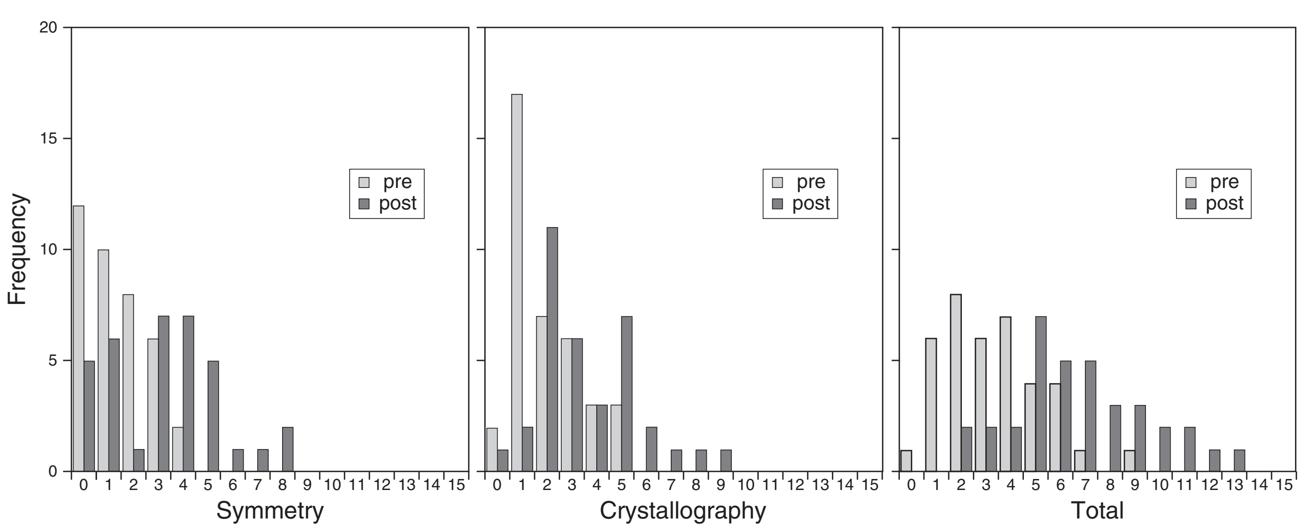


Figure 2. Distribution of pretest versus posttest scores by variable.

operations and point groups—to be confusing and difficult to conceptualize. As one student put it:

> My least favorite part of both the [group] theory and X-ray modules was learning about the point groups and reflection stuff; that was a little hard to understand and still is hard to grasp.

These qualitative observations are also supported by the quantitative data presented earlier. Although the pre–post comparisons reported in Table 1 were significant, the posttest scores show that there is room for a great deal of improvement as students scored an average of 6.74 points out of a possible 30. Students also would have liked more hands-on activities incorporated into the unit and less reliance on lecture.

Conclusion and Future Research

The primary goal of this project was to expose students to the important concepts of symmetry and crystallography by creating self-contained lessons that could be incorporated into a high school chemistry classroom. Although the unit had limitations, we believe this overall goal was achieved. Students were provided with an introduction to these important topics and demonstrated some conceptual understanding and retention of the material. We are currently working on revising the lessons to incorporate more hands-on activities and are actively exploring additional ways of more concretely presenting symmetry and crystallography to high school students.

It is important to note that the approach as originally designed and reported here may not be appropriate for all teachers, nor all classrooms. We recognize that many high school teachers may find it difficult to devote two weeks to materials that probably will not be tested on statewide science exams. However, we encourage teachers to use this work as a starting point in creating meaningful learning experiences for students in their own classrooms—learning experiences that convey just how rich and vibrant the field of chemistry is.

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Literature Cited

1. McKay, S. E.; Boone, S. R. *J. Chem. Educ.* **2001,** *78,* 1487–1490.
2. Hunter, A. D. *J. Chem. Educ.* **1998,** *75,* 1297–1299.
3. Vining, W. J.; Grosso, R. P. Jr. *J. Chem. Educ.* **2003,** *80,* 110.
4. Szalay, P. S.; Zeller, M.; Hunter, A. D. *J. Chem. Educ.* **2005,** *82,* 1555–1557.
5. Cass, M. E.; Rzepa, H. S.; Rzepa, D. R.; Williams, C. K. *J. Chem. Educ.* **2005,** *82,* 1736–1740.
6. Crouse, D. T. *J. Chem. Educ.* **2007,** *84,* 803–809.
7. Meyer, D. E.; Sargent, A. L. *J. Chem. Educ.* **2007,** *84,* 1551–1552.
8. Campbell, D. J.; Korte, K. E.; Xia, Y. *J. Chem. Educ.* **2007,** *84,* 1824–1826.
9. Dragojlovic, V. *J. Chem. Educ.* **1999,** *76,* 1240–1241.
10. Gawley, R. E. *J. Chem. Educ.* **2005,** *82,* 1009–1012.
11. Penn, R. L.; Flynn, L; Johnson, P. *J. Chem. Educ.* **2007,** *84,* 955–960.
12. Kahr, B. *Cryst. Growth Des.* **2004,** *4,* 3–9.
13. Rossi, M.; Berman, H. M. *J. Chem. Educ.* **1988,** *65,* 472–473.
14. Hohloch, J. M.; Grove, N.; Bretz, S. L. *J. Chem. Educ.* **2007,** *84,* 1530–1534.
15. Boyle, P. D. Crystal Growing for Students. *http://www.xray.ncsu.edu/student_xtal.html* (accessed Mar 2009).
16. Institute for Chemical Education, Optical Tranform Kit. *http://ice.chem.wisc.edu/Catalog/SciKits.htm#Anchor-Optical-13405* (accessed Mar 2009).
17. Bowen, C. W.; Bunce, D. M. *Chem. Educat.* **1997,** *2* (2).
18. Robinson, W. R.; Hurh, E. Using Conceptual Questions in the Chemistry Classroom. In *Survival Handbook for the New Chemistry Instructor,* Bunce, D. M., Muzzi, C. M., Eds.; Pearson Prentice Hall: Upper Saddle River, NJ, 2004.
19. *Statistical Package for the Social Sciences,* version 13; SPSS Inc.: Chicago, IL, 2005.

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- Assessment instruments