Continuous Symmetry & Chemistry Teachers: Learning Advanced Chemistry Content through Novel Visualization Tools

Inbal Tuvi-Arad
Department of Natural Sciences
The Open University of Israel
inbaltu@openu.ac.il

Ron Blonder
Department of Science Teaching
The Weizmann Institute of Science
Ron.Blonder@weizmann.ac.il

Abstract
In this paper we describe the learning processes of a group of experienced chemistry teachers in a specially designed workshop on molecular symmetry and continuous symmetry. The topic of continuous symmetry is a new field of study that provides a quantitative description of the distance of a specific structure from perfect symmetry. Using online interactive visualization tools, teachers were able to calculate continuous symmetry measures, with emphasis on the chemistry, rather than the mathematics of the calculations. Our results show that even a very basic knowledge of symmetry and continuous symmetry opens up new ways of thinking about and looking at molecules. The addition of visualization tools creates a deeper understanding of molecular structure and provides scaffolds for the learning processes. Moreover, familiarity with concepts of symmetry can help teachers understand and explain other topics such as chirality and polarity of molecules. Our results indicate that highly advanced content can influence the way teachers think, understand, and eventually teach. This experience can shed light on curriculum choices for teachers' education.

Keywords: Symmetry, Chemistry Teachers, Content Knowledge, Professional Development, Molecular Visualization.

Introduction
Many chemical phenomena are related to symmetry. Examples are molecular structure, chirality, polarity, reactivity, and spectroscopy. Symmetry is described in terms of elements (axes, planes, and points) and operations (rotation, reflection, and inversion). Traditionally, symmetry has been treated as a binary property – a given structure is either symmetric or not. In reality, exact symmetry is a rare beyond the atomic level. Inspection of molecular structures with highly sensitive analytical tools in modern chemistry shows again and again that structures that have classically been considered as symmetric actually are not. The continuous symmetry measure (CSM) (Pinsky, et al., 2008; Zabrodsky, Peleg, & Avnir, 1992, 1993) provides a quantitative description of the distance a particular structure has from perfect symmetry by means of a number, between zero and 100. In the last two decades, many correlations of the CSM with various physical and chemical properties of molecules were discovered (e.g., Alvarez, 2005; Cirera, Ruiz, Alvarez, Neese, & Kortus, 2009; Crippen, 2008; Glaser, 2008).

Despite its importance to understanding chemistry, symmetry is not an integral part of the high-school chemistry curriculum in Israel. Therefore, topics related to symmetry (e.g., chirality, polarity) are explained at a lower level of theory. Introducing chemistry teachers to symmetry can expand their view of molecular structure in general and broaden their theoretical knowledge concerning the topics of chirality and polarity, which they teach in class. Much literature on improving teaching and upgrading the professional status of teachers focuses on teachers'

Proceedings of the Chais conference on instructional technologies research 2010: Learning in the technological era
Y. Eshet-Alkalai, A. Caspi, S. Eden, N. Geri, Y. Yair (Eds.), Raanana: The Open University of Israel

knowledge (for example, see: Borko, 2004; Munby, Russell, & Martin, 2001). Shulman (1986, 1987) distinguished between three categories of teachers' knowledge: (1) subject matter content knowledge, (2) pedagogical content knowledge, and (3) curricular knowledge. The current paper focuses on the teachers' learning of an advanced topic in chemistry – symmetry and continuous symmetry, and the ways in which the teachers connected the newly learned topic (the new content knowledge) to the other two knowledge categories, namely, pedagogy knowledge and curricular knowledge.

Learning symmetry is based on the ability to visualize molecules in three-dimensions and to imagine their rotation and reflection in space. Research has shown that computerized tools for molecular visualization can lead to a better understanding of molecular structure in general (e.g., Barnea & Dori, 2000; Ferk & Yrtacnik, 2003; Kozma & Russell, 1997; Venkataraman, 2009) and symmetry in particular (e.g., Coleman & Gotch, 1998; Tuvi-Arad & Gorsky, 2007; Williamson & Jose, 2008). Furthermore, computerized visualization can facilitate learning of advanced topics which may look abstract and complicated when traditional teaching methods are used. The case of continuous symmetry is an example of such a topic. Here we describe a preliminary study aimed at exploring the influence of basic exposure to the concept of continuous symmetry in a technology enhanced environment on the general perception and understanding of molecular structure.

Research Design

This study was part of a teachers' professional program at the Weizmann Institute of Science aimed at development of high-level thinking skills and meta-cognition in chemistry learning. The symmetry part of the program was an 8 hours workshop that included two lectures – one on basic symmetry and the other on continuous symmetry, and two interactive tutorial sessions with online visualization tools and personal interviews. Lectures were given by the first author. The Molecular Symmetry Online website (http://telem.openu.ac.il/symmetry) was used to view molecules and their symmetry elements in three-dimensions. The CoSyM website (http://telem.openu.ac.il/symmetry/csm) was used to perform online calculations of CSMs and to visually compare the original molecule and the most symmetric one in three-dimensions. Interviews were conducted by both authors with the help of research assistants, during the final tutorial session, and took 20-30 minutes each. The interviews were tape-recorded and transcribed. In all tutorial sessions and interviews, the teachers worked in pairs.

Five exercises were developed. Exercises 1 and 2 reflect the pre-knowledge of the teachers prior to the workshop and will be considered as pre-exercises. Exercises 3 and 4 were designed for practice purposes and were given during the tutorial sessions after each lecture.

Exercise 5 was the interview. It included two problems that were based on applying the CSM theory using the CoSyM website. In the first question teachers were asked to predict whether the water and ammonia molecules has a C_2 rotation axis, a reflection plane and inversion point, and describe the hypothetical structure with an inversion point in each case. These predictions were then verified by calculating the corresponding CSM value and comparing the original molecule with the most symmetric structure provided by the website. In the second question they watched animations of symmetric and anti-symmetric vibrations of $XeOF_4$ and were asked to predict which symmetry elements are retained during vibration. Again, predictions were verified by calculations. The researchers encouraged the teachers to talk aloud and to explain their thinking during the exercise-solving process.

Twenty-one teachers participated in the symmetry workshop: 17 women and 4 men. Fourteen teachers were interviewed (7 pairs).

Methods

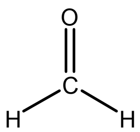
For this study, naturalistic inquiry methodologies involving qualitative data were used. The qualitative methodology is particularly useful for preliminary studies such as the one described here since it has the potential to discover trends and emerging hypotheses that can later be examined by statistical methods on a larger population in future research (Chi, 1997). Rather than separating out various aspects and examining them independently, we attempted to develop a holistic view of the workshop. The naturalistic interventions were designed to learn how the innovations affected the learning process (Brown, 1992). These allowed the researchers to follow the learning processes and to better understand the mutual interaction between the learners and the computerized environment.

Results

Exercises

Analysis of exercises 1 and 2 show that in general, the teachers' previous knowledge of symmetry prior to the workshop was rather limited. The average grade was 60 for each of these exercises. Most of the teachers were unable to fully identify symmetry elements and operations, even when formal definitions of these concepts were given to them. Table 1 presents examples of incorrect answers from question 1 of exercise 1. 76% of the teachers were wrong regarding this question. These answers clearly show that before the workshop teachers did not know the correct definition of symmetry.

Table 1. Examples of incorrect answers in question 1 of exercise 1

Question	Examples of incorrect answers
Is this molecule symmetric? Explain. 	• "No - there are two different atoms around the carbon – hydrogen and oxygen." • "No – the electronegativity of the three bonds, C-H and C=O is not the same." • "No – the carbon is not bonded to four groups. Even though there are two similar groups, the molecule is not symmetric." • "No – it is impossible to draw a plane that divides the molecule into two parts".

Exercises 3 and 4 were given to the teachers during the workshop in order to help them understand the basic concepts of symmetry and continuous symmetry. They focused on practice (as opposed to assessment) with as many examples as possible. The results in general were very good, with over 90% success for all questions.

Analysis of Interviews

The interviews were structured in the sense that teachers had to solve particular problems, and were guided by the interviewer. The aim was to have the participants describe their thinking during the process of problem solving and to reflect on their experience with the problems. Seven pairs of teachers were interviewed. Each question was graded according to the following scale: 2 – correct answer; 1 – correct after guidance from the interviewer; 0 – wrong answer. Table 2 presents the overall grades of the questions in exercise 5. Percentages are shown in parentheses. Of the seven pairs, one pair worked on different molecules in question 1; therefore, the results for question 1 are reported for the other six pairs.

Table 2. Total grades of the interview exercise

Question		Total grade (% correct answers)
1a Symmetry of water (N=12)	C_2 Rotation	12 (100)
	Reflection	12 (100)
	Inversion	7 (58)
	Predicted shape with inversion	10 (83)
1b Symmetry of ammonia (N=12)	C_2 Rotation	9 (75)
	Reflection	12 (100)
	Inversion	10 (83)
	Predicted shape with inversion	2 (17)
2a $XeOF_4$ symmetric vibration (N=14)	C_2 Rotation	14 (100)
	Reflection	14 (100)
	Generalization	7 (50)
2b $XeOF_4$ anti-symmetric vibration (N=14)	C_2 Rotation	14 (100)
	Reflection	9 (64)
	Generalization	8 (57)

In general most of the teachers were able to predict correctly the symmetry of the molecules in question 1. Difficulties appeared when they were asked to predict the shape of a hypothetical molecule with inversion symmetry (a line in the case of water, and a point in the case of ammonia). The case of ammonia was the most difficult structure to predict and only one pair solved the problem correctly. This may be attributed to the mathematical nature of the question, and the absence of chemical meaning of the resulting structure. Regarding the second question - loss of symmetry during vibration – most of the teachers predicted correctly which symmetry elements are retained in the vibration. However, not all of them acquired the generalization that if a vibration occurs on a particular symmetry element (e.g., a rotation axis or reflection plane), then that symmetry element is retained.

General Overview

All participants were fascinated by the new knowledge they had acquired at the workshop. We list here several citations of selected teachers who were interviewed.

- *"When I teach about molecular structure I describe only rigid structures. I never imagined that molecules move".*
- *"I had the picture of the plane in my head, but I was not able to share it with my friend. With the help of the site, I can now describe my thoughts."*
- *"I felt a big difference; the two sites helped me visualize a symmetry axis. The visualization opened my eyes".*
- *"Most of the time, molecules are not symmetric, and we didn't think about this before."*
- *"Now after I practiced with the websites, I have a new language to describe symmetry and everything is more organized for me."*
- *"Now I am going to look at molecules in a different way. There is no sharp distinction between symmetry and no symmetry – there are a lot of levels in the middle."*
- *"Electrons and atoms move all the time. Therefore, most of the time the symmetry is not ideal as we used to imagine it when we teach the subject."*

Discussion and Conclusions

The current research served as an opportunity to present a subject from the frontiers of chemistry research to high-school chemistry teachers in an enhanced visualization environment. As was evident from the teachers' quotes described above, the first interaction of the teachers with the concept of continuous symmetry expanded their view of the three-dimensional structure of molecules and intensified their understanding of molecular internal motion - vibration and rotation. Experience with calculations of the CSM opens up a new way of thinking about and looking at molecules. Performing CSM calculations is thus an effective tool for explaining the dynamic characteristics of molecules.

From a pedagogical point of view, the use of technology to teach continuous symmetry bridges between a rather intuitive chemical concept and advanced mathematics. The CoSyM website can thus serve as a learning environment for diverse audiences. Designed as an open tool, any molecule can be uploaded to the website, allowing users to control the content level.

Research has shown that difficulties in chemistry may be due to inadequate models at the molecular level (Kleinman, Griffin, & Kerner, 1987; Lijnse, Licht, Waarlo, & de Vos, 1990 and references therein; Tasker & Dalton, 2008). Yet, computerized molecular visualization tools can contribute to better understanding (Wu, Krajcik, & Soloway, 2001; Wu & Shah, 2004). Interactive three-dimensional visualization of molecules is an important feature of the CoSyM website. The ability to visually compare the original distorted structure with the most symmetric one obtained from the calculation, provides a visual meaning to the numerical result of the CSM and is a type of scaffold to the learning process (Kali & Linn, 2007, 2008). Furthermore, CSM calculations provide a scaffold for a more basic question - does a given molecule have a particular symmetry element? This was seen in the interviews when teachers used the CSM calculations to verify their prediction regarding inversion symmetry. In this sense CSM calculations serve as a direct technique to check the validity of a mental model,

Symmetry and continuous symmetry are not an integral part of the high-school chemistry curriculum in Israel. Nevertheless, teachers in our study made the connection to their everyday teaching processes in school. This result points out that highly advanced content can influence the way teachers think, understand, and eventually teach. However, exposing high-school teachers to pioneering chemistry, such as CSM, is not enough. There is a difference between being exposed to advanced knowledge and applying it in class. More research is needed in order to recognize the factors that can scaffold teachers in implementing up-to-date research topics in their teaching.

Acknowledgements

This research was supported by the Chais Research Center for the Integration of Technology in Education, at the Open University of Israel, grant no. 100901.

References

Alvarez, S. (2005). Polyhedra in (Inorganic) Chemistry. *Dalton Transactions, 13*, 2209-2233.

Barnea, N. & Dori, Y. J. (2000). Computerized Molecular Modeling: The New Technology for Enhance Model Perception among Chemistry Educators and Learners. *Chemistry Education: Research and Practice in Europe, 1*, 109-120.

Borko, H. (2004). Professional Development and Teacher Learning: Mapping the Terrain. *Educational Researcher, 33*(8), 3-15.

Brown, A. L. (1992). Design Experiments: Theoretical and Methodological Challenges in Creating Complex Interventions in Classroom Settings. *Journal of the Learning Sciences, 2*(2), 141.

Chi, M. T. H. (1997). Quantifying Qualitative Analyses of Verbal Data: A Practical Guide. *Journal of the Learning Sciences, 6*(3), 271-315.

Cirera, J., Ruiz, E., Alvarez, S., Neese, F., & Kortus, J. (2009). How to Build Molecules with Large Magnetic Anisotropy. *Chemistry - A European Journal, 15*(16), 4078-4087.

Coleman, S. L., & Gotch, A. J. (1998). Spatial Perception Skills of Chemistry Students. *Journal of Chemical Education, 75*(2), 206-209.

Crippen, G. M. (2008). Chirality Descriptors in Qsar. *Current Computer-Aided Drug Design, 4*(4), 259-264.

Ferk, V. & Yrtacnik, M. (2003). Students' Understanding of Molecular Structure Representations. *International Journal of Science Education, 25*(10), 1227-1245.

Glaser, R. (2008). Chiral Recognition Via Helical Sense and Phase in a Crystalline Supramolecular Array of Intermeshed Triple-Helices. *Chirality, 20*(8), 910-918.

Kali, Y. & Linn, M. C. (2007). Technology Enhanced Support Strategies for Inquiry Learning. In J. M. Spector, M. D. Merrill, J. J. G. V. Merriënboer & M. P. Driscoll (Eds.), *Handbook of Research on Educational Communications and Technology* (3rd ed., pp. 445-490). Mahwah, NJ: Erlbaum.

Kali, Y. & Linn, M. C. (2008). Designing Effective Visualizations for Elementary School Science. *Elementary School Journal, 109*(2), 181-198.

Kleinman, R. W., Griffin, H. C., & Kerner, N. K. (1987). Images in Chemistry. *Journal of Chemical Education, 64*, 766.

Kozma, R. B. & Russell, J. (1997). Multimedia and Understanding: Expert and Novice Responses to Different Representations of Chemical Phenomena. *Journal of Research in Science Teaching, 34*(9), 949-968.

Lijnse, P. L., Licht, P., Waarlo, A. J., & de Vos, W. (Eds.). (1990). *Relating Macroscopic Phenomena to Microscopic Particles*. Proceeding of the Conference at Utrecht centre for science and mathematics education, University of Utrecht.

Munby, H., Russell, T., & Martin, A. K. (2001). Teachers' Knowledge and How It Develops. In V. Richardson (Ed.), *Handbook of Research on Teaching*, 4th ed., pp. 877-904. Washington, DC: American Educational Research Association.

Pinsky, M., Casanova, D., Alemany, P., Alvarez, S., Avnir, D., Dryzun, C., et al. (2008). Symmetry Operation Measures. *Journal of Computational Chemistry, 29*(2), 190-197.

Shulman, L. S. (1986). Those Who Understand: Knowledge Growth in Teaching. *Educational Researcher, 15*, 4-14.

Shulman, L. S. (1987). Knowledge and Teaching - Foundations of the New Reform. *Harvard Educational Review, 57*(1), 1-22.

Tasker, R. & Dalton, R. (2008). Visualizing the Molecular World – Design, Evaluation, and Use of Animations In J. K. Gilbert, M. Reiner & M. Nakhleh (Eds.), *Visualization: Theory and Practice in Science Education* (Vol. 3, pp. 103): Springer Netherlands.

Tuvi-Arad, I. & Gorsky, P. (2007). New Visualization Tools for Learning Molecular Symmetry: A Preliminary Evaluation. *Chemistry Education Research and Practice, 8*(1), 61-72.

Venkataraman, B. (2009). Visualization and Interactivity in the Teaching of Chemistry to Science and Non-Science Students. *Chemistry Education Research and Practice, 10*(1), 62-69.

Williamson, V. M. & Jose, T. J. (2008). The Effects of a Two-Year Molecular Visualization Experience on Teachers' Attitudes, Content Knowledge, and Spatial Ability. *Journal of Chemical Education, 85*(5), 718-723.

Wu, H. K., Krajcik, J. S., & Soloway, E. (2001). Promoting Understanding of Chemical Representations: Students' Use of a Visualization Tool in the Classroom. *Journal of Research in Science Teaching, 38*(7), 821-842.

Wu, H. K. & Shah, P. (2004). Exploring Visuospatial Thinking in Chemistry Learning. *Science Education, 88*(3), 465-492.

Zabrodsky, H., Peleg, S., & Avnir, D. (1992). Continuous Symmetry Measure. *Journal of the American Chemical Society, 114*(20), 7843-7851.

Zabrodsky, H., Peleg, S., & Avnir, D. (1993). Continuous Symmetry Measures .2. Symmetry Groups and the Tetrahedron. *Journal of the American Chemical Society, 115*(18), 8278-8289.