Using Technology to Support the Development of Conceptual Understanding of Chemical Representations

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Abstract: Many students have difficulty learning symbolic and molecular chemical representations. This study investigates how students develop their understanding of chemical representations with the aid of a visualizing tool, eChem, that allows them to build molecular models and view multiple representations simultaneously. Multiple sources of quantitative and qualitative data were collected with the participation of seventy-three eleventh graders in a high school over a six-week period. The results of the pre- and post-tests showed that students' understanding of chemical representations improved after using eChem (t=13.9, p<.001, effect size= 2.68). Students who engaged in thoughtful discussions made conceptual and visual connections between 2D and 3D models, identified structural difference between representations, and demonstrated deep understanding of representations in interviews. Evidence also indicates that some features of the visualizing tool helped students construct models and translate representations. Compared with the spacefill and wireframe models, the ball-and-stick model was the most concrete and visualizable one for these high school students. The results of the study suggested that both physical and computational models could serve as a thinking vehicle for students to manipulate mentally. The mental images helped students to translate representations and identified structural differences of organic compounds.

Keyword—Chemical representations, visualization, eChem

1. Introduction: For a considerable time, educational researchers have paid much attention to the topic of chemical representations because many students have difficulty moving from symbolic chemical representations to the nature of chemical or physical properties. Most well known in this area is the work of Gabel, Samuel and Hunn (1987) who defined three levels of understanding in chemistry: macroscopic, microscopic, and symbolic. Complimentary research to Gabel et al's work (e.g. Ben-Zvi, Eylon, & Silberstein 1986) has shown that learning of microscopic and symbolic representations is especially difficult for students, since these representations are invisible and abstract while students' understandings of chemistry relies heavily on sensory information. Therefore, new approaches to teaching chemistry were developed using technological tools and concrete models.

The computer generated visualizing tool used in the present study, eChem, is designed to play a central mediating role in chemistry instruction by allowing students to build molecular models and view multiple representations simultaneously. Visualizing with eChem refers to the ability beyond the perception of seeing. When students "visualize" a molecular structure, they can generate its chemical meanings beyond the lines, dots and symbols shown on paper. This study explores how, with the aid of eChem, students develop their ability to translate chemical representations, whether they make connections between these representations, and what supports their ability to do so. The research questions are: 1) Are students able to translate between two-dimensional and three-dimensional representations? If so, in what ways does eChem help students to translate multiple representations of chemistry? 2) What patterns do

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Note: Preference for presentation—Talk or Poster.

students demonstrate while translating chemical representations and constructing models by using eChem? 3) What kinds of chemical meanings are generated by students when they visualize the molecular structures?

2. Theoretical background: Chemical representations are the elements of chemistry language (Hoffman & Laszlo, 1991); chemists use them to communicate with their colleagues and to do science inquiry (Kozma, Chin, Russell & Marx, 1997). However, the literature indicates that most students are unable to visualize the microscopic and symbolic representations as experts do (e.g., Ben-Zvi, Eylon, & Silberstein, 1986; Gabel et al., 1987; Kozma & Russell, 1997) and are incapable of completing the model-to-formula translations (Keig & Rubba, 1993).

Various instructional and learning strategies are used to ease these learning difficulties, and the increased use of physical or computational models is striving to achieve this goal. Research supports the advantages of manipulating physical models that include helping students to visualize invisible atoms and molecules, and promoting long term understanding (Copolo & Hounshell, 1995; Gabel & Sherwood, 1980). Technological tools that integrate multiple representations provide students with opportunities to visualize chemistry and promote conceptual understanding (Kozma & Russell, 1997). Based on empirical findings of their studies, Kozma and his colleagues (Kozma et al., 1997) state that the use of multiple, linked representations helped students understand chemical equilibrium and its related concepts.

While empirical studies assert the value of using models and technological tools for chemistry learning, however, little is understood about how models actually support a student's learning, how a student's use of these models evolves and changes during instruction in classroom settings, and what features of a technological tool support students to develop conceptual understanding of chemical representations. Although many professional visualizing tools have been developed for chemistry (Crouch, Holden, & Samet, 1996), none were designed for high school use. Thus, this study explores how high school students develop understanding of chemical representations by using a technological tool with similarities to professional tools.

3. Technological tool—eChem: The technological tool used for this study was eChem, a simplified and learner-centered design version of professional visualizing tools, developed by the Center for Highly Interactive Computing in Education (hi-ce) at University of Michigan. eChem guides students in three main actions—*Construct*, *Visualize* and *Analyze*. The *Construct* function allows students to create organic molecular structures, view them from all possible angles, and manipulate them more easily than physical ball-and-stick models (see Fig. 1). The *Visualize* function provides students with multiple views of different molecules and various representations such as ball-and-stick, wire-frame and space-fill simultaneously (see Fig. 2). On the *Analyze* function, students can make connections between molecular models at the microscopic level (molecular structures) and their collective behaviors at the macroscopic level (chemical and physical properties). It integrates multiple representations to aid students of different learning styles to choose their preferred symbol systems and create internal representations (Salomon, 1979). Graphic interfaces allow students to switch among actions easily and facilitate visual engagement. Furthermore, eChem allows students to revise their models and create their own database of compounds over time.

4. Methods:

4.1 Context—This study was conducted in an alternative public high school in an urban university town in the Midwest. The teachers in the science program have been working with educational researchers from a local university to develop and implement a three-year, project-based science curriculum (Marx, Blumenfeld, Krajcik, & Soloway, 1997). Seventy-three eleventh graders in three sections participated (n=73, 36 females) and were taught by three different teachers. The students in this study had a range of ethnic backgrounds, academic abilities, and socioeconomic levels, although the majority of students were white, middle- to upper middle-class.

The use of the tool, eChem, was integrated into a six-week project called the Toxin Project. In this project, students worked in small groups and selected a known toxin to investigate from a list provided by the teachers. Three learning activities were designed to explore three main actions of eChem, introduce the definitions of hydrocarbons and IUPAC (International Union of Pure and Applied Chemistry) nomenclature of organic compounds, and visualize two-dimensional (2D) and three-dimensional (3D) chemical representations.

4.2 Data Collection—Quantitative data was collected from all participants. Qualitative data was collected on eighteen students (three pairs in each section), who were nominated as the target students based on their gender, ethnic backgrounds, learning performances in the past two years, and ability to verbalize their learning process. All data was collected over a six week period.

4.3 Data Analysis—Pre- and post-tests, including multiple choice and short answer questions, were used to evaluate students' conceptual understanding of chemical representations before and after using eChem. To obtain the students' explanations and meanings for representations and to investigate students' understanding, we conducted semi-structured interviews after students finished this project. The interview questions focused on students' conceptions of the relationship between microscopic and macroscopic representations and abilities of translating representations. Video recordings of target students while using eChem provided details about how target students used this visualizing tool and allowed the researchers to hear conversations of target students, analyze their activities, and record the time they spent on each action in eChem. Artifacts, including worksheets of eChem activities, models built by eChem, and webpages designed for final presentations, demonstrated students' learning progress over time.

Cases were created for each pair of focus students, and cross-case analysis was used for determining the commonalties, differences and difficulties of translating representations and model construction. To draw conclusions, the data analysis involved generating assertions by searching the data corpus, establishing an evidentiary warrant for the assertions and verifying assertions by confirming and disconfirming evidence.

5. Findings:

5.1 Quantitative part—Students' conceptual understanding of chemical representations improved after using eChem. Although this study did not include a control group and the learning effects by instructions and the use of the technological tool were inseparable, the data shows a significant difference in the pre- and post-test score (t=13.9, p<.001, effect size = 2.68).

5.2 Qualitative part—A number of themes related to students' engagement, conceptual understanding, and the use of eChem emerged from the qualitative data analysis and synthesis.

<u>*5.2.1 Engagement and conceptual understanding*</u> The higher the engagement with the use of eChem, the deeper the conceptual understanding of chemical representations. This finding was

supported by the analysis of video recordings and interview transcripts. High engagement students consciously made conceptual and visual connections between representations while using eChem. For example, to make meanings of 3D models, these students rotated a propane model from Fig. 3 (A) to Fig. 3 (B), because the structure (B) was visually similar to the linear 2D structural formula on paper. In addition, high engagement students were more sensitive to structural differences between various representations. A brief discussion between one student dyad of how to name a chemical compound in eChem activity II demonstrated the process of visualizing a condensed formula (Fig. 4). In order to name a compound, they had to identify the longest carbon chain first; however, a condensed structural formula was not a representation that they were familiar with. As one student attempted to relate CH3 on the condensed formula to methane, this student's partner assisted her to visualize the four-carbon chain by verbally externalizing how he pictured CH3 as a carbon atom attaching to three hydrogen atoms. Through the discussion and the process of drawing out this formula, this student differentiated her conceptions of methane and CH3 on condensed structural formulas, and conceptually connected CH3 to a methyl-like group rather than methane.

While the frequency analysis indicated that the frequency of discussions was almost the same among all target dyads, there was a range of the amount of time spent on discussions. Analysis of video recordings revealed that discussions that high engagement students had involved more content knowledge and endured for longer time.

5.2.2 Models as a thinking vehicle Both physical and computational models served as a thinking vehicle for students to manipulate models mentally. In response to questions that probed students' understanding of structural differences between two structural formulas, the majority of target students formed and manipulated 3D models mentally. For example, another student said,

> Those are different (see Fig. 5). Now I'm picturing the examples like Mark [the teacher] did with the little models [physical models] with the springs. You can't turn it [Fig. 5 (A)] like here the chlorine and CH3. They are on the opposite sides you know. Here [Fig. 5 (B)] is on the same side. You can't just turn it, because the double bond doesn't work that way; you can't just twist it.

To translate various representations, some of them formed a mental image prior to drawing a 2D model. During the interview, in order to translate a chemical formula, C_5H_{10}, to a structural formula, one student (S1) compared this formula with the general formula of alkanes, and then transformed this formula to a mental image of what C_5H_{10} may look like.

> *(The interviewer shows them a chemical formula, C_5H_{10}, and asks them translate it to a structural formula.)*
> S1: is it cyclopentane? *(Looking at S2.)*
> S2: what?
> S1: It's like a circle. *(Using figures to make a circle.)* It's not pentane, because it's C five, H twelve.
> Interviewer: How do you know that?
> S2: Because the formula for it, is it 2n+2?
> S1: If you get carbons, two hydrogens attach each carbon, except the ends. *(Using one hand to show a linear carbon chain, and moving the other hand to locate where hydrogen atoms are around this chain.)*
> S1: I am thinking cyclopentane, because there aren't extra two.

Based on various alkane models built during eChem activity I, this student and his partner (S2) generated the general formula of alkanes by themselves. The excerpt above indicated that they developed a conceptual linkage between formulas and structures, which included the information of symbols, structures, and mental images. They retrieved the relevant information to make formula-to-model translation, and demonstrated their understanding by elaborating the idea of general formula and externalizing their mental models through verbal and non-verbal interactions with the interviewer.

5.2.3 Three-dimensional models Among three types of models eChem provided, the ball-and-stick model was the most concrete and visualizable one for these students. Analysis of artifacts indicated that the majority of dyads provided ball-and-stick models as their 3D models on final presentations. Additionally, interview transcripts indicated that ball-and-stick models were more helpful for students to identify functional groups and make translations than spacefill or wireframe models. While wireframe models may be too abstract by showing only carbon chains, and spacefill models do not demonstrate bond orders directly, conveying the visible information of atoms and bond orders may make ball-and-stick models the most concrete ones.

5.2.4 Feature analysis Some features in eChem helped students construct models and translate representations. Video recordings showed that the majority of students frequently used model rotation to make empty bonding sites visible. As mentioned previously, model rotation also helped students visually connect 2D and 3D representations. The chemical formula displayed on the *Construct* page assisted students in identifying empty bonding sites and translating a structural formula into a 3-D model. Some features, however, were never used. When encountering technical problems, none of students read the Help message—a feature designed to scaffold the learning process.

6. Conclusion: By using the visualizing tool, eChem, for six weeks, the majority of eleventh graders were able to translate between two-dimensional and three-dimensional representations. Their abilities of identifying functional groups, describing structural differences, and translating representations significantly improved. We also found that several features in eChem, such as model rotation and chemical formula, helped students construct models and translate representations. Some students frequently engaged in thoughtful discussions and compared structural differences between various representations. These discussions involved both visual and conceptual aspects of representations, which in turn may deepened these students' understandings of representations. Translations between representations appeared to involve different levels of understanding of chemical principles. The interview data indicated that students who were able to translate 3D to 2D models may or may not be able to translate chemical formula to structural formula. The later translation process might entail both visual and conceptual understandings, while the 3D-to-2D translation could be achieved by solely comparing visual features of these models. For future investigation, we would explore whether and how the *Analysis* feature of eChem facilitates students to make conceptual connections between representations at the macroscopic and microscopic levels.

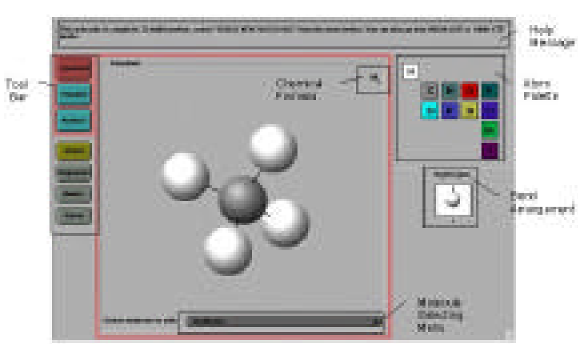


Fig. 1 Construct page

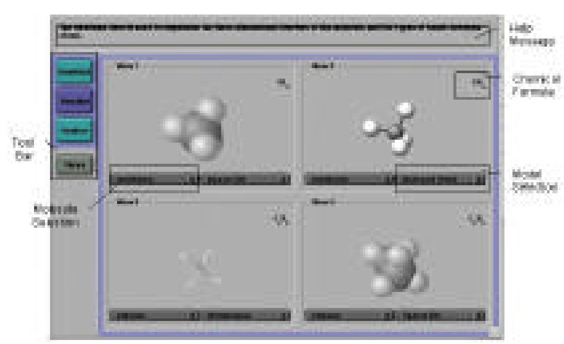
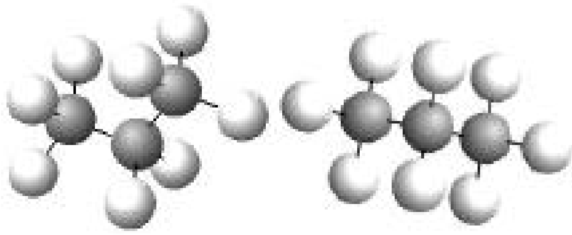


Fig. 2 Visualize page



(A) **(B)**

Fig. 3 Two propane models

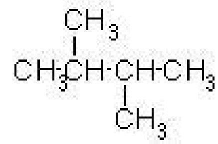
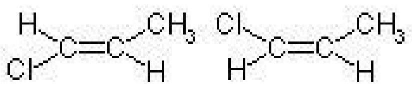


Fig. 4 Condensed structural formula of 2, 3-dimethyl butane



(A) **(B)**

Fig. 5 Trans- and cis-isomers

References:

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1986). Is an atom of copper malleable? Journal of Chemical Education, 63, 64-66.

Berger, C., Walton, C., Jones, T., & Wurman, P. (1995). The Event Recorder (Version 5.6). Ann Arbor, Michigan: The University of Michigan.

Copolo, C. F., & Hounshell, P. B. (1995). Using three-dimensional models to teach molecular structures in high school chemistry. Journal of science education and technology, 4(4), 295-305.

Crouch, R. D., Holden, M. S., & Samet, C. (1996). CAChe molecular modeling: A visualization tool early in the undergraduate chemistry curriculum. Journal of Chemical Education, 73(10), 916-918.

Gabel, D. L., Samuel, K. V., & Hunn, D. (1987). Understanding the particulate nature of matter. Journal of Chemical Education, 64, 695-697.

Gabel, D., & Sherwood, R. (1980). The effect of student manipulation of molecular models on chemistry achievement according to Piagetian level. Journal of Research in Science Teaching, 17(1), 75-81.

Hoffmann, R., & Laszlo, R. (1991). Representation in chemistry. Angewandte Chemie, 30, 1-16.

Keig, P. F., & Rubba, P. A. (1993). Translation of representations of the structure of matter and its relationship to reasoning, gender, spatial reasoning, and specific prior knowledge. Journal of Research in Science Teaching, 30(8), 883-903.

Kozma, R. B., Chin, E., Russell, J., & Marx, N. (1997). The roles of representations and tools in the chemistry laboratory and their implications for chemistry instruction (Technical report). Menlo Park, CA: SRI International.

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, 949-968.

Marx, R. W., Blumenfeld, P. C., Krajcik, J. S., & Soloway, E. (1997). Enacting project-based science. Elementary School Journal, 97(4), 4-13, 22.

Salomon, G. (1979). Interaction of media, cognition and learning. San Diego, CA: Jossey Bass.