Increasing Representational Fluency with Visualization Tools

Mike Stieff, Michelle McCombs, University of California-Davis, One Shields Avenue, Davis, CA 95616
mstieff@ucdavis.edu, mrmccombs@ucdavis.edu

Abstract: The present article reports on the use of one visualization tool, Connected Chemistry, to increase chemistry student's representational fluency, or use of accepted chemical representations and reasoning from submicroscopic perspectives. The tool was embedded in a unit on the particulate nature of matter and implemented in three high school classrooms. Analysis of learning via pre-post test measures revealed a significant increase in representational fluency among all Connected Chemistry students compared to students learning from more traditional lecture-and-text method; however, comparable improvements in declarative knowledge were not evident.

Visualization Tools for Teaching Science

Increasingly, visualization tools show promise for improving learning and achievement in science. Such tools are varied in structure and function and include a range of technologies that provide animations of physical objects (e.g., Wu, Krajcik, & Soloway, 2001), models of scientific data (e.g., Wu et al., 2001), and simulators of dynamic systems (e.g., Wilensky, 1999). An equally diverse array of theoretical frameworks motivates the design and use of visualization tools in the classroom. For example, some tools illustrate imperceptible phenomena (Stieff & Wilensky, 2003), others model authentic scientific investigations (Reiser *et al.*, 2001), and still others allow students to manipulate scientific data (Edelson, Gordin, & Pea, 1999). Concerted efforts to validate the use of these tools have revealed their potential both in research settings and in genuine classrooms. Here, we report on the development of one visualization tool, Connected Chemistry, and its potential to support learning in high school chemistry.

Connected Chemistry utilizes a suite of molecular-level simulations of chemical phenomena (e.g., http://education.ucdavis.edu/~stieff/Assets/DiscoveringMatter/DiscoveringMatter.html). Designed in the NetLogo modeling environment (Wilensky, 1999), Connected Chemistry offers students direct access to the submicroscopic objects and phenomena under study in chemistry. As such, Connected Chemistry simulations teach chemistry from the perspective of emergent phenomena (Wilensky, 2001). That is, the simulations emphasize how the submicroscopic interactions between molecular objects result in macroscopic concepts and symbolic representations learned in the classroom. Students can manipulate various parameters of Connected Chemistry simulations to make predictions based on their understanding and then compare their observations with their predictions. By facilitating the iterative process of observe-predict-test, Connected Chemistry offers students with the opportunity to engage in the same processes of inquiry that define scientific practice (NRC, 1996).

Previously, several studies have reported on four particular benefits of Connected Chemistry for improving student learning in chemistry (Levy & Wilensky, 2004; Stieff & Wilensky, 2003). First, Connected Chemistry simulations help students clarify and strengthen their conceptual understanding of fundamental chemistry concepts. Second, with Connected Chemistry students can simulate macroscopic laboratory experiments to isolate fundamental factors that describe a concept. Third, Connected Chemistry offers simultaneous presentations of the submicroscopic, macroscopic, and symbolic representations used in chemistry to better connect molecular interactions, concepts, and chemical representations for students. Finally, Connected Chemistry supports a greater sense of ownership of scientific knowledge by providing students with learning opportunities outside of textbooks.

The results from these previous investigations suggest that similar affordances of Connected Chemistry may be realized when embedded in a classroom curriculum. Typical high school chemistry curricula do not provide students with direct access to the molecular world. Instead, students must rely on two-dimensional diagrams or verbal representations, which creates a considerable barrier to learning about the dynamic interactions of atoms and molecules (Gilbert, 2005). Connected Chemistry offers one avenue to address this barrier by (1) supporting reasoning about dynamic interactions at the submicroscopic level and (2) illustrating the use of accepted chemical representations. Taken together, these skills comprise a students' *representational fluency* in chemistry, which is necessary for students' to reason about fundamental chemistry objects and concepts using canonical symbolic representations.

Improving Representational Fluency with Connected Chemistry

Presently, we have explored students' development of representational fluency while learning about the particulate nature of matter. To that end, we have embedded a Connected Chemistry simulation in a guided inquiry activity, *Discovering Matter!*, and implemented the activity in three high schools. *Discovering Matter!* was developed by a work circle of researchers, chemists, and high school teachers. Work circles combine the expertise of teachers and educational researchers through all stages of curriculum development and assessment. The approach has been particularly effective in the development and sustained implementation of several computer-based science curricula (e.g., Reiser *et al.*, 2000).

Structure of The *Discovering Matter!* Activity

Discovering Matter! includes three modules that students can complete in three 40-minute sessions. In the *Laboratory Module*, students perform a standard laboratory experiment. Here, students explore and observe macroscopic chemical phenomena commonly observed in the laboratory. To improve the flexibility of the activity, Connected Chemistry does not mandate experiments, but suggests options to provide teachers several choices based on their needs and resources. In the *Simulation Module*, pairs of students explore a Connected Chemistry simulation to understand the nature of the submicroscopic interactions responsible for macroscopic observations. Here, each pair completes a guided inquiry exploration of the simulation in which they make predictions and draw representations of submicroscopic objects and interactions. In the *Discussion Module*, the teacher and students link the submicroscopic and macroscopic levels. Here, the teacher guides students to reflect on their observations from the laboratory and simulation to understand how important concepts emerge from molecular interactions.

In *Discovering Matter!* students use a Connected Chemistry simulation in concert with a laboratory experiment on physical and chemical change to learn about the particulate nature of matter. This topic is typically covered early in instruction and forms the foundation of modern chemistry. In the activity, students classify elements, compounds, and mixtures according to the composition and behavior of submicroscopic particles. Students have significant difficulty understanding this fundamental concept as the relationship between particle behavior and macroscopic observations is not directly apparent (Johnstone, 1993). Indeed, students as well as chemistry student teachers are often unable to accurately define the concept or illustrate it with accepted chemical representations (Calik & Ayas, 2005).

Context of the Present Study

The work circle implemented and assessed *Discovering Matter!* in three classrooms at different schools with largely different populations. Edgewater High (Mr. Drake), located in a low-SES urban community, serves a primarily Hispanic and White student body and has a statewide rank in the 4th decile. Shadylane (Mr. Thorp) High, located in a middle-class urban community, serves a primarily Asian and Hispanic student body and ranks in the 7th decile. Finally, Lakeview High (Mrs. Kraft), located in an affluent suburban community, serves a primarily White student body and ranks in the top decile (10th). The workcircle conducts development and assessment activities with these sites deliberately to develop a self-contained curriculum that meets the needs of diverse populations and schools.

For the present study, differences in the implementation of Connected Chemistry (CC) occurred at each site. Mr. Drake and Mrs. Kraft both began with a lecture to introduce the use of simulations and followed with the simulation and discussion modules. Neither Mr. Drake's nor Mrs. Kraft's classrooms completed a laboratory module. At Shadylane, students first performed a laboratory experiment on chemical and physical changes. Mr. Thorp then introduced the simulation via lecture and his students completed the simulation module. Throughout the discussion module Mr. Thorp used macroscopic demonstrations to help the students connect their observations of the simulations with those of the laboratory. Each teacher also taught a lesson on the particulate nature of matter to a comparison class (NoTool) using lecture-and-text methods. All classes received five days of instruction on the topic.

Assessing Representations Fluency via Connected Chemistry

Learning outcomes were assessed via pre- and post-test measures. All students completed the pre-test one day before and the post-test three days after instruction. The 10-item measure included a variety of items that asked students to define relevant terms, classify different types of matter, and draw particle-level representations. Given space constraints, the present analysis addresses the overall test score and two items (7 and 10) that required the generation of chemical representations. Each item is summarized here and detailed analyzed below. Figures 1 and 2 illustrates examples of Items 7 and 10, respectively.

Item 7. Draw a submicroscopic picture of a heterogeneous mixture. Explain your drawing in words.

Item 7 assessed (1) knowledge of mixtures and (2) submicroscopic representation of mixtures. Briefly, correct responses included the definition of a heterogeneous mixture (i.e., a non-uniform mixture of two or more substances) and a representation of particles constituting a heterogeneous mixture.

Item 10. Water can exist as both steam and ice. Draw a submicroscopic picture of liquid water, steam, and ice. Explain, in words, each of your drawings.

Item 10 assessed (1) knowledge of particle motion in the states of matter and (2) submicroscopic representation of the states. Correct responses stated that water molecules in ice vibrate in close proximity, in liquid water they slide past one another in close proximity, and in steam they move with high velocity and large distances between particles. Correct representations illustrated these relationships *and* indicated that water molecules maintained the same chemical composition regardless of state.

Two work circle members assessed the measures using a 30-point scale. Comparison of the independent scores yielded 98% agreement on 3700 items. Disagreements were resolved uniformly by discussion. After initial scoring, Items 7 and 10 each received two additional binary scores according to whether the given answer contained (1) an accepted chemical representation and (2) a submicroscopic drawing. Item 7 also received (1) a binary score according to whether the representation was *heterogeneous* and (2) a binary score according to whether the definition was a *heterogeneous*.

Results & Discussion

The present analysis addresses overall performance and improvement in representational fluency via use of submicroscopic reasoning and accepted chemical representations.

Overall Learning Gains

Table 1 summarizes the total scores for each classroom. Using post-test score as a final outcome measure, the dataset was analyzed via a 2 (curriculum) x 3 (teacher) ANCOVA with pre-test score as the covariate. Controlling for pre-test score, the analysis revealed a main-effect of curriculum, $F(1,175) = 17.64$, $p < 0.001$). Across schools CC students scored slightly higher ($M = .62$, $SD = .14$) than NoTool students ($M = .60$, $SD = .17$). The analysis indicated a main-effect of teacher, $F(2,175) = 4.08$, $p = .018$; in addition, an interaction between curriculum and teacher was observed, $F(2,175) = 4.51$, $p = .012$. For each teacher, analysis of post-test scores via ANCOVA revealed the nature of the detected interaction. No significant differences were observed between the CC and NoTool students at Lakeview, $F(1,63) = 0.60$, $p = .44$. Significant differences were observed at Edgewater High, $F(1,49) = 7.24$, $p = .01$, and Shadylane, $F(1,61) = 10.8$, $p = .002$.

Table 1. Mean scores on pre-post test measures for each school and curriculum

	Lecture-and-Text		Connected Chemistry	
School	Pre-Test (n)	Post-Test (n)	Pre-Test (n)	Post-Test (n)
Lakeview	0.39 ± 0.17 (34)	0.64 ± 0.15 (32)	0.27 ± 0.14 (34)	0.59 ± 0.12 (35)
Edgewater	0.50 ± 0.16 (27)	0.54 ± 0.20 (27)	0.41 ± 0.16 (25)	0.54 ± 0.11 (26)
ShadyLane	0.45 ± 0.19 (31)	0.60 ± 0.16 (30)	0.44 ± 0.18 (35)	0.70 ± 0.14 (34)

Note. Mean scores are indicated for each class ± 1*SD*.

Further inspection of Table 1 clarifies the impact of Connected Chemistry on achievement. Across schools, Connected Chemistry yielded a negligible gain (0.13). At individual sites, however, gains were varied: no gain was observed at Lakeview, a small gain (.25) was observed at Edgewater, and a moderate gain (.62) was observed at

Shadylane. Note that the analysis controls for prior knowledge and indicates that despite equivalent post-test scores at Edgewater, CC students gained more learning with the simulations than NoTool students did from their texts. Field observations of the implementation suggest causal mechanisms for these site-specific outcomes. Of the three schools, Shadylane students alone completed a simulation, discussion, *and* laboratory module. Moreover, Mr. Thorp conducted macroscopic demonstrations of several reactions simulated in Connected Chemistry for whole-class discussion. Conversely, NoTool students at Lakeview completed a modeling activity (Remington, 1980) and a drawing activity to practice using chemical representations. Our preliminary conclusion is that the additional activities at Shadylane and Lakeview, and the lack of a laboratory module at Edgewater, may explain the site-specific differences between classrooms.

Although the gains as measured by total score for the three sites was negligible, the gross analysis does not adequately address representational fluency. Rather, a detailed inspection of student inscriptions is needed to clarify the use of submicroscopic reasoning with accepted chemical representations.

Reasoning with submicroscopic representations

A detailed inspection of student responses on Items 7 and 10 reveals significant differences in the use of submicroscopic reasoning, as evidenced by the number of submicroscopic representations used (Table 2). Analysis via logistic regression revealed that CC students were more likely to draw submicroscopic phenomena in answer to test items than NoTool students. On Item 7, 89% of CC students drew submicroscopic representations compared to 76% of NoTool students, $\chi^2(1, N = 177) = 5.09$, $p = .02$. On Item 10, 98% of CC students drew representations at the sub-microscopic level compared to 87% of NoTool students, $\chi^2(1, N = 184) = 9.24$, $p = .02$.

Table 2. Total students using submicroscopic representations on Item 7 and Item 10

	Item 7		Item 10	
Curriculum	Submicroscopic	Other	Submicroscopic	Other
Lecture-and-text	65	20	77	12
Connected Chemistry	82	10	93	2

Figure 1 illustrates sample answers taken from a CC and a NoTool student for Item 7, which asks students to define a heterogeneous mixture and draw a submicroscopic example. In the example, both students provided accurate definitions, and both drew acceptable representations of heterogeneous mixtures; however, their two answers reflect reasoning at different levels of perspective. To illustrate a heterogeneous mixture, the NoTool student drew a macroscopic picture of a basket of apples and plums and the CC student drew a submicroscopic picture of copper atoms and water molecules.

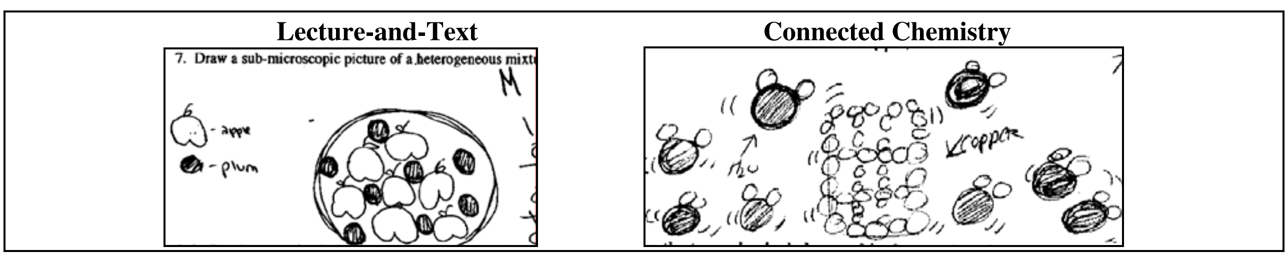

Figure 1. A macroscopic drawing (NoTool) and a submicroscopic drawing (CC) to Item 7.

The macroscopic example is a common example seen in chemistry texts. While the drawing indicates that the basket contains noticeably different objects throughout, it does not communicate the level of detail in the submicroscopic drawing of the CC student. The CC student has accurately represented the nature of a heterogeneous mixture. Her drawing illustrates two types of particles in different phases: the copper atoms remain vibrating together immersed in the flowing water molecules. Although the NoTool student provided an accurate definition and common drawing, when viewed from the system-level, he has actually represented a homogenous mixture: the two fruits are uniformly distributed throughout the basket. As such, it is not apparent that the NoTool students possesses the more accurate understanding of heterogeneous mixtures communicated by the CC student.

Illustrating phenomena with accepted chemical representations

Further inspection of the representations used on Items 7 and 10 reveals that CC students were more likely to use accepted chemical representations of submicroscopic objects, as in Table 3. On Item 7, 66% of CC students used an accepted chemical representation compared to 27.5% of NoTool students, $\chi^2(1, N = 159) = 24.63$, $p < .001$. Likewise on Item 10, 93.7% of CC students used accepted chemical representations compared to 60.7% in NoTool classrooms, $\chi^2(1, N = 101) = 32.70$, $p < .001$.

Table 3. Student use of acceptable chemical representations on Item 7 and Item 10

	Item 7		Question 10	
Curriculum	Generic	Chemical	Generic	Chemical
Lecture-and-Text	50	19	35	51
Connected Chemistry	30	60	6	89

Figure 2 illustrates examples of the different quality of representations used by CC and NoTool students on Item 10, which requires an illustration of how water molecule behavior changes among states. As in the example above, both students have provided acceptable representations that indicate the particle-level differences in each state. The NoTool student has used generic circles to represent water molecules; however, the CC student has used the correct space-filling models that highlight each atom in the molecule. Such examples were common among CC students, and likely reflect their increased exposure to such representations in the simulations.

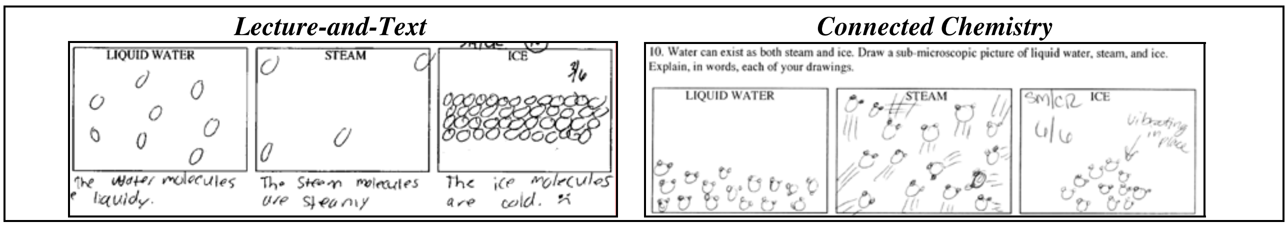

Figure 2. Sample representations on Item 10 from students in lecture-and-text and Connected Chemistry.

A closer look at Figure 2 illustrates a more striking difference between the students: The CC student has correctly illustrated the motion of the particles that result in macroscopic observations. In the figure, the CC student has used small lines and text to indicate the differences in molecular motion in steam and ice relative to liquid water. Conversely, the NoTool student has illustrated the relative differences of particle distance in each state, but has not referenced molecular motion, which fundamentally determines state. Moreover, the NoTool student's description of each panel refers to macroscopic level reasoning. For example, the student states that "The steam molecules are *steamy*", thus attributing macroscopic characteristics to the submicroscopic objects. Such confusions were common among NoTool students, and suggest that they did not understand the information embedded in acceptable chemical representations as accurately as CC students.

Acquisition and Application of Declarative Knowledge

Although significant increases in the use of submicroscopic reasoning and accepted chemical representations were evident, it was not apparent that CC students made significant gains in declarative knowledge after completing *Discovering Matter!*. Analysis of the accuracy of definitions and representations to reflect heterogeneous mixtures on Item 7 clarifies the issue. Table 4 summarizes the raw number of students who used accurate heterogeneous definitions and representations. Analysis via logistic regression revealed no significant differences between the percentage of NoTool (41%) and CC (33%) students who provided a heterogeneous definition, $\chi^2(1, N = 194) = 1.69$, $p = .19$. Likewise, no significant differences were found between the percentage of NoTool (46%) and CC (37%) students who drew a heterogeneous representation, $\chi^2(1, N = 184) = 1.61$, $p = .20$.

Table 4. Student use of heterogeneous definitions and representations on Item 7.

	Definition		Representation	
Curriculum	Other	Heterogeneous	Other	Heterogeneous
Lecture-and-text	56	40	48	41
Connected Chemistry	66	32	60	35

Together with the above analyses, this last finding indicates that CC students increased their use of accepted chemical representations at the submicroscopic level, but they may not have significantly improved their fundamental knowledge of chemistry. For example, CC students were more likely to draw space-filling diagrams on Item 7; however, those diagrams often represented homogenous mixtures, single molecules, and pure substances. Such responses were equally likely in NoTool classrooms, where students responded incorrectly with abstract symbols or macroscopic diagrams. In sum, both groups acquired only a minimum understanding of the nature of heterogeneous mixtures, or general concept of the particulate nature of matter, as reflected in the low grand mean (.60) on total post-test score.

General Discussion

An inability to relate symbolic and imagistic representations to fundamental domain concepts is a primary difficulty in chemistry that may underlie many misconceptions and problem solving errors (Johnstone, 1993; Gilbert, 2005). The above analyses indicate that Connected Chemistry activities may address this challenge by improving representational fluency. That is, the activities improve learning by supporting students' reasoning with accepted submicroscopic chemical representations. As seen in the present study, teachers that combine laboratory, discussion, and simulation activities achieve the greatest gains with Connected Chemistry. The illustrated examples also suggest that Connected Chemistry can help students resolve "levels confusion" (Wilensky & Resnick, 1999) in chemistry. Namely, Connected Chemistry helps students to relate events on the submicroscopic level to observations on the macroscopic level without misattributing properties across levels. Levels confusion has been implicated as a source of difficulty in other science domains, and its impact in chemistry is now being explored.

The present work also suggests the limitation of visualization tools. Our analysis suggests that representational fluency did increase among Connected Chemistry students; however, declarative knowledge did not. This finding may be expected given that the *Discovering Matter!* activity provided a disproportionate amount of time on visual representations compared to terminology: Each teacher used less than 10 minutes to discuss the term "heterogeneous", and students were given no supporting materials outside of the classroom activity. Consequently, Connected Chemistry students may simply have not realized which type of mixture was defined by the term. The equally poor performance of the lecture-and-text students underscores the need for further curriculum development efforts, likely supported by visualization tools, to improve learning in chemistry. Building on these findings, we are continuing to optimize Connected Chemistry activities for use in diverse settings and to further explore the potential of visualization tools for increasing representational fluency and understanding in chemistry.

Reference List

Calik, M., & Ayas, A. (2005). A comparison of level of understanding of eight-grade students and science student teachers related to selected chemistry concepts. *Journal of Research in Science Teaching*, *42*(6), 638-667.

Edelson, D. C., Gordin, D. N., & Pea, R. D. (1999). Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences*, *8*(3/4), 391-450.

Gilbert, J. K. (2005). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 1-27). Dordrecht: Springer.

Johnstone, A. H. (1993). The development of chemistry teaching. *Journal of Chemical Education*, *70*(9), 701-705.

Levy, S. T., & Wilensky, U. (2004, April). Connected chemistry - a study of secondary students using agent-based models to learn chemistry. In U. Wilensky, & S. Papert (Eds.), Networking and complexifying the science classroom: Students simulating and making sense of complex systems using the Hubnet networked architecture. *Symposium conducted at the annual meeting of the American Educational Research Association*, San Diego, CA.

National Research Council [NRC]. (1996). *National science education standards*. Washington, D.C.: National Academy Press.

Reiser, B. J., Spillane, J. P., Steinmuller, F., Sorsa, D., Carney, K., & Kyza, E. (2000). Investigating the mutual adaptation process in teachers' design of technology-infused curricula. In B. Fishman, & S. O'Connor-Divelbiss (Eds.), *Proceedings of the fourth international conference of the learning sciences* (pp. 342-349). Mahwah, NJ: Erlbaum.

Reiser, B. J., Tabak, I., Sandoval, W. A., Smith, B., Steinmuller, F., & Leone, T. J. (2001). Bguile: Strategic and conceptual scaffolds for scientific inquiry in biology classrooms. In S. M. Carver, & D. Klahr (Eds.), *Cognition and instruction: Twenty-five years of progress* (pp. 263-305). Mahwah, NJ: Erlbaum.

Remington, L. D. (1980). Teaching the nuts and bolts of chemistry. *Science Teacher*, *47*(9), 35-37.

Stieff, M., & Wilensky, U. (2003). Connected chemistry - incorporating interactive simulations into the chemistry classroom. J*ournal of Science Education and Technology*, *12*(3), 285-302.

Wilensky, U. (1999). *Netlogo* (Version 3.0) [Computer Program]. Evanston, IL: Center for Connected Learning and Computer Based Modeling, Northwestern University.

Wilensky, U. (2001). Modeling nature's emergent patterns with multi-agent languages. P*aper presented at the EuroLogo 2001*, Linz, Austria.

Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems perspective to making sense of the world. J*ournal of Science Education and Technology*, *8*(1), 3-18.

Wu, H.-k., Krajcik, J. S., & Soloway, E. (2001). Promoting conceptual understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching*, *38*(7), 821-842.