[In *Journal of Computers in Mathematics and Science Teaching, 21*(3), 253-279]

Learning Chemistry Through the Use of a Representation-Based Knowledge Building Environment

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ABSTRACT

Many students leave high school chemistry courses with profound misunderstandings about the nature of matter, chemical processes, and chemical systems. The ChemSense project is addressing this problem through a multidisciplinary program of research and development to examine the impact of representational tools, chemical investigations, and discourse on chemistry learning and teaching in high schools and colleges. This work intersects several theoretical approaches to learning, including collaborative project-based investigations, representational competence, knowledge building, and the design of chemistry curriculum. The ChemSense Knowledge Building Environment allows students and instructors to collaborate in the investigation of chemical phenomena, collect data, build representations of these phenomena, and participate in scaffolded discourse to explain these phenomena in terms of underlying chemical mechanisms. Research indicates that ChemSense is effective in supporting student representational use and chemical understanding. In this paper, we present our theoretical approach, describe the ChemSense learning environment in the context of actual use by high school students, summarize our research findings, and discuss the implications of these findings for future work.

INTRODUCTION

Many students leave high school chemistry courses with profound misunderstandings about the nature of matter, chemical processes, and chemical systems (Krajcik, 1991). In 1995, the Third International Mathematics and Science Study found that the science scores of U.S. secondary school seniors were among the lowest of all 21 nations participating in the study of secondary science achievement. For 68% of U.S. high school students, chemistry is the last science course they take in high school (National Center for Education Statistics, 2001), and for many, it is the last science course they will ever take. At the same time, learning in science and mathematics has become even more crucial, with implications that range from everyday decision-making in a scientifically complex world to national economic competitiveness in an increasingly global market (National Commission on Mathematics and Science Teaching for the 21st Century, 2000).

In response, national organizations, state departments of education, institutions of higher education, school districts, and educators have considered and adopted a range of goals to improve student learning in science in elementary through postsecondary education (National Science Foundation, 1996; National Research Council, 1996; Spencer, 1999; Paulson, 1999). Among these are:

- All students should be expected to attain a high level of scientific competency.
- All students should have access to supportive, challenging programs in science, mathematics, and technology, and all students should acquire literacy in these subjects by direct experience with the methods and processes of inquiry.
- Students should thoroughly learn a limited number of science and mathematics concepts rather than lightly touch on many.

- Curricula should stress understanding, reasoning, and problem-solving rather than memorization of facts, terminology, and algorithms.
- Teachers should engage students in meaningful activities that regularly and effectively employ calculators, computers, and other tools in the course of instruction.

To advance these goals, we have undertaken a multidisciplinary program of research and development that examines the impact of representational tools and chemical investigations on chemistry learning and teaching in high schools and colleges. This project, called ChemSense, involves a team of chemists, cognitive scientists, computer scientists, and science educators focusing on three critical and interrelated issues: chemical understanding, scientific investigations, and discourse and representation. This work intersects several theoretical approaches to learning, including collaborative project-based investigations (Krajcik, Blumenfeld, Marx, Bass, Fredricks, & Soloway, 1998; Crawford, Marx & Krajcik, 1999), representational competence (Kozma & Russell, 1997), the design of chemistry curriculum (Coppola, 1999), and knowledge building (Scardamalia & Bereiter, 1996; Coleman, 1998; diSessa, 1993; Greeno, Benke, Engle, Lachapelle, & Wiebe, 1998; Schommer, 1993). ChemSense includes a set of tools (software and probeware) and curriculum activities that draw on this theory to scaffold students' learning of chemistry. These tools and activities are based on designs by curriculum integration teams of researchers, chemists, teachers, and developers, informed by learning theory, and grounded in authentic classroom use (Schank, Kozma, Coleman, & Coppola, 2000).

RATIONALE

Our work draws on situative theory (Greeno, 1998; Brown, Collins & Duguid , 1989; Resnick, 1988), which characterizes understanding and learning in terms of people's participation in practices of inquiry and discourse that include interactions with others and with the material, symbolic, and technological resources in their environment. The focus of this theory is on participation in processes that construct knowledge. These processes are shaped but not determined by the constraints and affordances of interaction with physical and social systems. The affordances and constraints of physical systems—including equipment and representational systems—are those characteristics that permit or inhibit certain activities or cognitions that can be performed in the use of these systems. We extend situative theory to include the practice of scientific inquiry and the role of representations and discourse in collaborative investigations and we apply this theory to the learning of chemistry. When viewed within this theoretical context, scientific inquiry is seen as an emergent, transactional process among and between scientists and the materials at hand that include physical/chemical substances, instruments, and representations. Learning is characterized as becoming attuned to constraints and affordances of activity and becoming more centrally involved in the practices of a community.

In the chemistry laboratory, perceptual changes in chemical substances afford chemists an understanding that "something has happened," but often this understanding is constrained by the lack of features that convey the underlying mechanisms that account for these perceptual changes. Representations, both those generated by scientists and those generated by their instruments, are among the physical systems historically constructed by the scientific community to support the understanding of chemical entities and processes. These representations, along with the discourse and meaning-making activities of the chemistry community, have resulted in significant advances in the understanding of chemical constructs, such as molecular geometry, connectivity, aggregation, state, and concentration (Coppola, 1999). The features of various representations, singularly and together, afford certain ways of thinking and talking about underlying entities and processes that advance the inquiry process and scientific understanding (Kozma, 1999; Kozma, Chin, Russell, & Marx, 2000).

Students, in contrast, typically do not have the representational or discourse skills that support the inquiry practices of scientists (Kozma & Russell, 1997). For example, students do not connect what they observe in the laboratory with their notions of microscopic entities and processes (Gabel, 1998). High school and even college students often have profound misconceptions of what underlies physical phenomena (Krajcik, 1991; Nakhleh, 1992). Students of all ages seem to have trouble understanding and using the scientifically accepted model that matter is made of discrete particles that are in constant motion and have empty space between them (Nakhleh, 1992). Nor are students particularly skilled in their use of chemical representations of various sorts (Kozma & Russell, 1997). Furthermore, Coleman (1998) points out that in their discourse students often make and defend vacuous claims and rarely produce explanations or justifications for their answers.

The features of different representations afford different ways of thinking and talking about the phenomena they represent. The use of multiple representations in combination can support a more complete understanding of a phenomenon (Kozma, Russell, Jones, Marx, & Davis, 1996). Molecular-level, or nanoscopic, diagrams and animations have often been proposed as a way to support student understanding in chemistry (Burke, Greenbowe & Windschitl, 1998; Sanger &

Greenbowe, 2000). The rationale is that features of these illustrations make visible otherwise abstract chemical concepts, especially those related to the particulate nature of matter. Diagrams are used to convey entities and states, such as characteristics of elements, compounds, and mixtures, or of liquids, solids, and gases. Animations illustrate processes such as equilibrium and electrolysis. However, research in the cognitive laboratory (Morrison & Tversky, 2001) indicates that comprehension of animations is problematic. The fleeting nature of the animated image and the minute changes that are happening simultaneously reduce students' ability to comprehend them. Students are ill prepared to attend to the conceptually important features of the animation.

There is evidence that *student generation*, rather than presentation, of graphics addresses the comprehension problem. In a study by Gobert and Clement (1999) in earth science, students who created diagrams of what they learned about plate tectonic processes outperformed students who wrote summaries of their learning, on subsequent measures of causal and dynamic reasoning. The results of this study suggest that the process of creating and manipulating dynamic representations, such as animations, might support students' reasoning about issues of moment-by-moment sequences of events and causality that they otherwise fail to comprehend when merely observing an animation.

There is also evidence that the use of instrument-generated dynamic representations—such as real-time graphs—in the context of collaborative investigations of physical phenomena increases both students' understanding of the phenomena and of the representations of them (Kelly & Crawford, 1996). The real-time connection between physical phenomena and their representations afford the ability to experimentally manipulate these phenomena and observe changes in the representation. The discourse that surrounds the observations of both the phenomena and the representations affords an understanding of the moment-by-moment connections and their meaning. The role of social discourse is crucial to this process of understanding. When students are engaged in collaborative activity in which they are manipulating and explaining dynamic representations, they can more readily achieve convergent understanding through discursive interchange (Roschelle, 1992). However, without adequate skills and support, students often spend most of their time discussing task management, only superficially addressing scientific concepts (Krajcik et al., 1998; Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999).

Krajcik et al. (1998) proposes a model of project-based investigation and a set of classroom activities that can organize students' investigations, representational use, and discourse. With this model, students are engaged in posing research questions, designing investigations that would address these questions, constructing apparatus and collecting data, analyzing data and drawing conclusions, and presenting findings. Each stage of this model will promote and benefit from student discourse and use of representations. Student presentations are perhaps the most public component of the Krajcik model; however, the entire process can benefit from public sharing.

Public documentation of students' questions and scientific ideas through the shared construction of artifacts by a variety of means, including networking tools (Chan, Burtis, & Bereiter., 1997; Roth, 1996), help students "make connections among perspectives, ask questions of one another, and observe their revisions over time" (Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999). Building and acting on shared knowledge, particularly when embodied in representations, provides learners with the opportunity to align their attention, coordinate their perceptions, and converge their ideas about the scientific explanations they construct.

Once student work and interaction are made public, teachers can establish and maintain the social norms of classroom discourse and practice that center on the use of representation and peer collaboration (Lemke, 1990). To create these norms, teachers can serve as both models and guides (Crawford, 2000). Specifically, teachers can themselves model the use of representations in their own ways of communicating about chemistry; they can model progressive, inclusive discussion practices; and they can model effective use of tools and resources. By providing high-level resources for both the understanding of chemistry and the skill to collaborate effectively, teachers both model and guide the types of support students can give one another in their collaborative efforts.

Drawing on this theory and research, we have developed a computer-based learning environment and associated activities to increase students' chemical understanding and representational skills. This system, called ChemSense, enables the use of multiple representations in the context of collaborative laboratory investigations among a community of students engaged in chemistry knowledge building. It also employs the use of instrument-generated dynamic representations, specifically real-time graphs of chemical experiments. The real-time connection between physical phenomena and their representations afford students the ability to experimentally manipulate these phenomena and observe changes in the representation. Students are provided with these representational tools in the context of activity structures that support classroom social systems engaged in chemical inquiry. Our underlying hypothesis is that the use of these representational tools during the conduct of collaborative chemical investigations supports students' convergent discourse in which they come to understand the entities and processes that underlie chemical phenomena.

The remainder of this paper is organized as follows. First, we describe our approach to curriculum activities, including the underlying content themes and investigation-based framework, and introduce two curriculum modules—Solubility and Soap—developed by our team of teachers, chemists, and researchers. Next, the ChemSense software is presented within the context of actual tasks from the Solubility module and with real products produced California high school students using this module. Then we summarize our research findings from classroom use at a California high school and the University of Michigan, and from teacher use in a Texas A&M summer workshop. Finally, we discuss the implications of our findings for future work.

THE CHEMSENSE CURRICULUM FRAMEWORK

The ChemSense approach to curriculum activities builds on the National Science Education Standards (Center for Science, Mathematics, and Engineering Education, 1995) to develop skills in inquiry, scientific discourse and explanation, and content knowledge related to structure and properties of matter and chemical reactions. The content component is designed around a set of five temporal or spatial dimensions that we have identified as associated with the particulate nature of matter and chemical reactions: change in (a) connectivity, (b) molecular geometry, (c) aggregation, (d) state, and (e) concentration (see Table 1). Taken together, these dimensions begin to portray the molecular world imagined by chemists to account for observable phenomena. All involve changes in molecular and supramolecular structure that correspond to critical aspects of chemical reactivity. In addition, these time-dependent dimensions cut across more traditional chemical topics, such as acid-base reaction, electrochemistry, solubility, kinetics, and thermodynamics. The ChemSense environment provides an opportunity for learners to reveal their emerging understanding of this content at an unprecedented level of sophistication, and to do so equally well within their peer community and with their instructors.

The ChemSense activity structure also draws heavily on Krajcik’s (Krajick et al., 1998) model of project-based investigation in which students pose research questions, design investigations that address these questions, construct apparatus and collect data, analyze the data and draw conclusions, and present their findings.

Table 1. Five key dimensions related to chemical change.

Connectivity. The connectivity of atoms to make molecule structures sits at the core of contemporary chemistry. Chemical identity is expressed in terms of the molecular structure. Patterns of observations on many thousands of sophisticated chemical examples have led to one of the most important advances in chemistry: the structure-reactivity relationship. Chemical reactions, that is, the transformation of one set of compounds to another, are changes in chemical identity and are expressed in terms of connectivity changes. These patterns of connectivity are often associated with certain perceptual qualities of a compound.

Molecular Geometry/Shape. Molecular structure involves more than connectivity; molecules also have shape. And chemical changes involve more than changes in connectivity. A complete understanding of chemical reactivity also involves understanding the changes in spatial relationships that accompany chemical change‹‹changes in shape. Sometimes, changes in shape influence greatly the understanding of the chemical process. Changes in biochemical systems are a good example. Other times, the changes take place and there is no particular impact.

State. The state of a molecule within a set of molecules is the full inventory of energy relationships that exist. Heat and light are the two most common sources of energy that influence changes in state. Phase change is an example, where the relationship between molecules depends on the temperature of the environment. When molecules absorb or emit light, this process also involves a change in state.

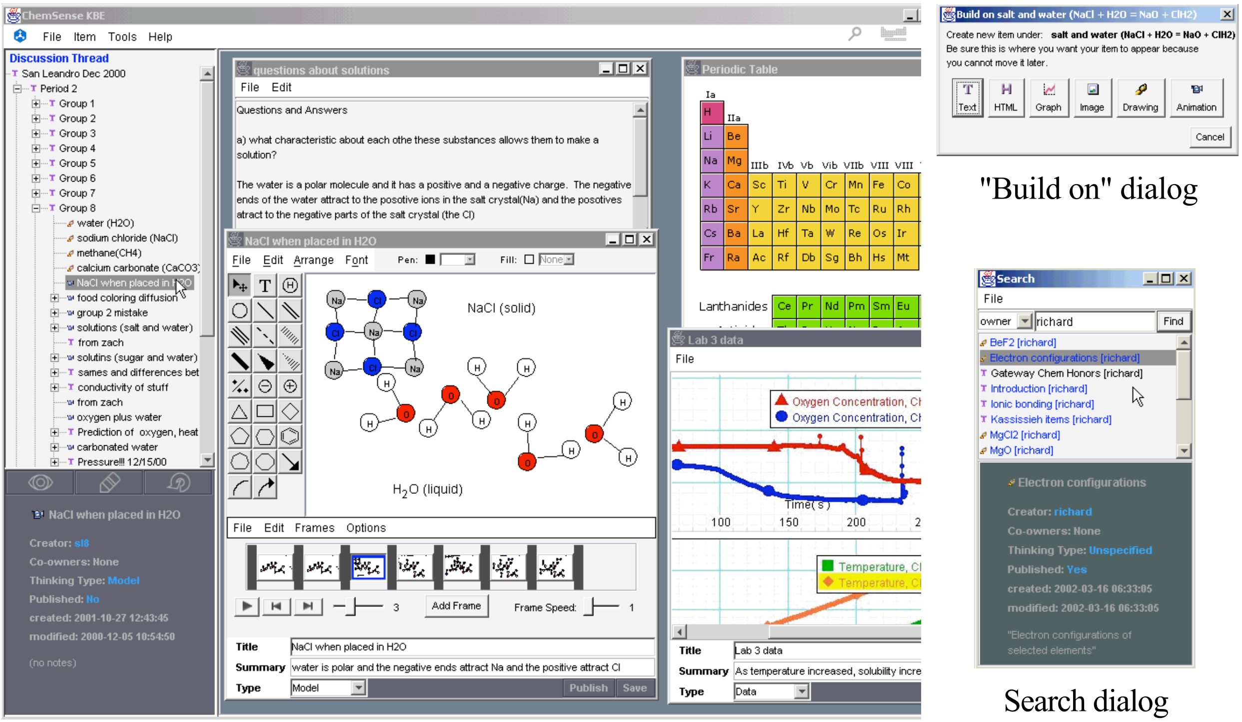
Aggregation. The aggregation of molecules is influenced by a variety of intermolecular and intramolecular interactions. Why do some salts dissolve in water and others do not? Why do some things mix while others do not? Forces of aggregation also strongly influence our understanding of biochemistry because, in general, multiple molecular units must spontaneously assemble in order for specific chemical reactions to be catalyzed. An understanding of drug design, including mode of action, relies heavily on understanding the relationships that exist in molecular clusters.

Concentration. When materials combine to undergo chemical reactions, large collections of molecules mix, colliding with one another. All measures of concentration express "the number of molecules per unit volume." Changes in concentration affect the number of collisions that can take place between the different substances. The higher the concentration, the more molecules of one substance will be able to collide with those of another. The greater the number of collisions, the greater the likelihood that a productive collision takes place. The effect of concentration on reactions is an important topic in understanding the particulate nature of matter.

At present, ChemSense includes two complete, multi-week modules: Solubility and Soap. These modules are designed to help students connect observations of phenomena with both macroscopic and nanoscopic representations, and examine these connections to explain observable phenomena in terms of the underlying mechanisms. The Solubility module covers a wide range of concepts: vapor pressure and solution equilibrium, molecular solvation, and factors affecting solubility, miscibility, dispersion, and colligative properties of solutions. Geometry is the predominant dimension that governs the underlying mechanisms in the Solubility module. These mechanisms—namely, the physical interaction of individual molecules—help underscore the drawing and animation functions of ChemSense and their usefulness in helping students communicate time-dependent chemical ideas. The Soap module focuses on understanding that the complex chemical process of saponification can be understood by focusing on more discrete concepts—mixing of substances, chemistry of water, solubility, hydrophobicity, hydrophilicity—and then synthesizing these ideas. Aggregation and connectivity are the predominant dimensions represented in the Soap module.

THE CHEMSENSE LEARNING ENVIRONMENT

The ChemSense Knowledge Building Environment (KBE) is virtual workspace for students to express and discuss ideas in chemistry (see Figure 1). The KBE provides tools to support student generation of chemistry representations, as well as support for discussion and knowledge building. More specifically, the KBE supports the sharing, viewing, and editing of a variety of representations, including text, images, graphs, molecule drawings, and animations. Students and instructors can annotate existing items, create new items that build on others' work, classify items by semantic type (as in CSILE; Scardamalia & Bereiter, 1996), and export their work in Web format for application in other venues (e.g., for Web-based presentations. Laboratory investigations are currently supported through the use of separate PASCO probeware and software for real-time data collection (e.g., dissolved oxygen, pH, temperature) and data display.



Discussion Thread
- San Leandro Dec 2000
  - Period 2
    - Group 1
    - Group 2
    - Group 3
    - Group 4
    - Group 5
    - Group 6
    - Group 7
    - Group 8
      - water (H2O)
      - sodium chloride (NaCl)
      - methane(CH4)
      - calcium carbonate (CaCO3)
      - NaCl when placed in H2O
      - food coloring diffusion
      - group 2 mistake
      - solutions (salt and water)
      - from zach
      - solutins (sugar and water)
      - sames and differences bet
      - conductivity of stuff
      - from zach
      - oxygen plus water
      - Prediction of oxygen, heat
      - carbonated water
      - Pressure!!! 12/15/00

NaCl when placed in H2O
Creator: sl8
Co-owners: None
Thinking Type: Model
Published: No
created: 2001-10-27 12:43:45
modified: 2000-12-05 10:54:50
(no notes)

questions about solutions

Questions and Answers

a) what characteristic about each othe these substances allows them to make a solution?

The water is a polar molecule and it has a positive and a negative charge. The negative ends of the water attract to the posotive ions in the salt crystal(Na) and the posotives atract to the negative parts of the salt crystal (the Cl)

NaCl when placed in H2O

Title: NaCl when placed in H2O
Summary: water is polar and the negative ends attract Na and the positive attract Cl
Type: Model

Title: Lab 3 data
Summary: As temperature increased, solubility incre
Type: Data

Build on salt and water (NaCl + H2O = NaO + ClH2)

Create new item under: **salt and water (NaCl + H2O = NaO + ClH2)**
Be sure this is where you want your item to appear because you cannot move it later.

"Build on" dialog

Search

owner: richard
- BeF2 [richard]
- Electron configurations [richard]
- Gateway Chem Honors [richard]
- Introduction [richard]
- Ionic bonding [richard]
- Kassissieh items [richard]
- MgCl2 [richard]
- MgO [richard]

Electron configurations
Creator: richard
Co-owners: None
Thinking Type: Unspecified
Published: Yes
created: 2002-03-16 06:33:05
modified: 2002-03-16 06:33:05
"Electron configurations of selected elements"

Search dialog

Figure 1. The ChemSense Knowledge Building Environment (KBE) with item browsing area (upper left), preview pane (lower left), and workspace. (This workspace shows real products created by students at a California high school.)

How the ChemSense KBE Works

The ChemSense KBE is written entirely in Java and features a cross-platform client-server architecture. That is, the client views and edits files that are stored on a central server, and an

Internet connection and login account is required to use the software. Although all files are stored on the server, students and instructors can export data from ChemSense to their local computer.

Once logged in to the ChemSense KBE, the student[1] is presented with a large single-window application containing an item browsing area, a preview pane, and a class workspace in which multiple items can be viewed, each within their own internal window (see Figure 1). This windowing strategy exploits the benefits of multiple windows (e.g., allowing users to compare and contrast the content from many items side-by-side) while still providing a single window organizer that affords fast access to navigation and preview functions (Shneiderman, 1998).

The browser pane presents a tree outline of related items, similar to the organization of a threaded discussion board. Just as replies in a threaded discussion board are indented under the original postings, documents in the ChemSense KBE are linked and indented under the items they build on. When an item is expanded, the ChemSense client makes a request (over the Internet) to the ChemSense server to retrieve the children of that item for display. When an item is selected, more information about it appears in the "preview pane" just below the browser. Here students can learn who created the item, what its "thinking type" (a semantic label such as hypothesis, data, method, etc.) is, when it was created and last modified, and whether or not it is published (a way of signaling to others that work on an item is complete). When an item is viewed or edited (e.g., by pressing the View or Edit buttons[2]), it appears in a new window in the workspace area. Only the creator[3] of an item can edit it, and they can do so as often as desired. All items posted in a classroom workspace

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[1] Instructors also have login accounts and can use all of the features of the Chemsense described here. For brevity, we sometimes use the term "student" in place of "student or instructor."

[2] Right-click, keyboard, and/or menu shortcuts are available for these and most other actions in ChemSense.

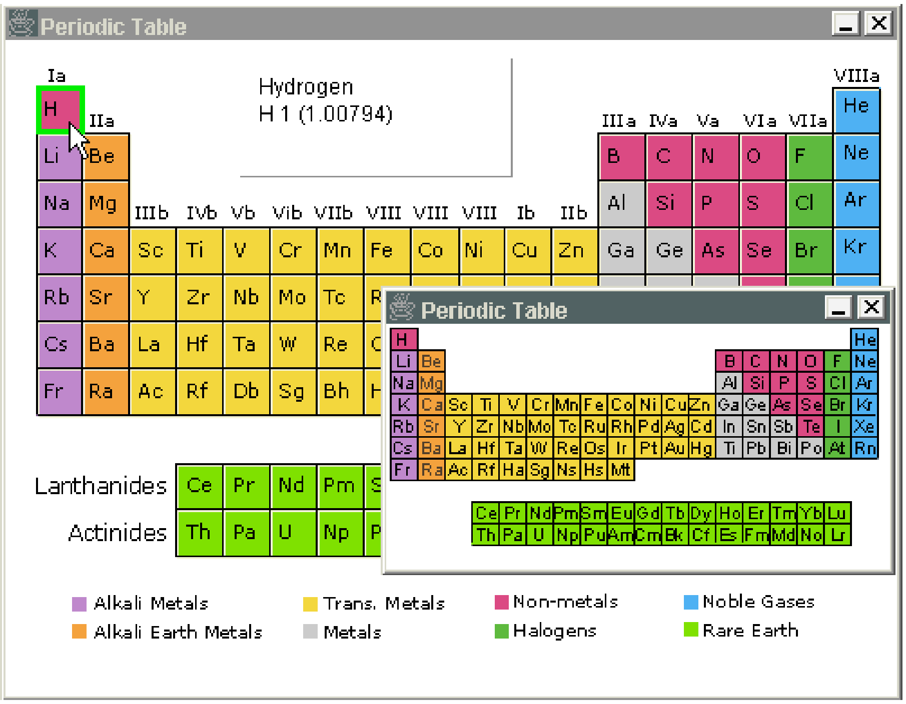
[3] The creator of an item is also known as the item's "owner". Co-ownership of an item is also supported, which means multiple login accounts can edit an item if co-ownership permission is explicitly granted on an item.

are viewable by others who use that workspace. Students can also search for items by title or owner, and preview, view, or edit items from the search dialog (see Figure 1, bottom right).

New items are created by "building on" an existing item (cf. Scardamalia & Bereiter, 1996). This is done by selecting or opening an item and then pressing the Build On button. The student can then choose one of several editing tools presented in the Build On dialog (see Figure 1, top right). An editor for the new item's content and properties (including title, thinking type, and summary) is then presented. Once saved, the item appears in the tree, indented, below the item that it was built upon, and ChemSense sends the contents and properties over the Internet to the central server for storage. When satisfied with an item's content, students are encouraged to publish it by pressing the Publish button. Published items appear in blue type, signaling to others that this work is finished.

Representation Construction Tools

The ChemSense KBE offers a variety of construction tools for text, images, drawings, animations, and graphs. All of the tools support import from local files and export to local files via the tool's File menu. Supported file formats include standard Web formats (text, GIF and JPEG images, Quicktime) and ChemSense's internal formats (in most cases, XML). It also provides large and small periodic tables reference tools (Figure 2) in which users can select an element for more information (i.e., atomic number and weight). Below we describe each of the construction tools in more detail, in the context of actual use and with real products created by high school juniors in California working on the Solubility module. Student names have been changed to preserve confidentiality.



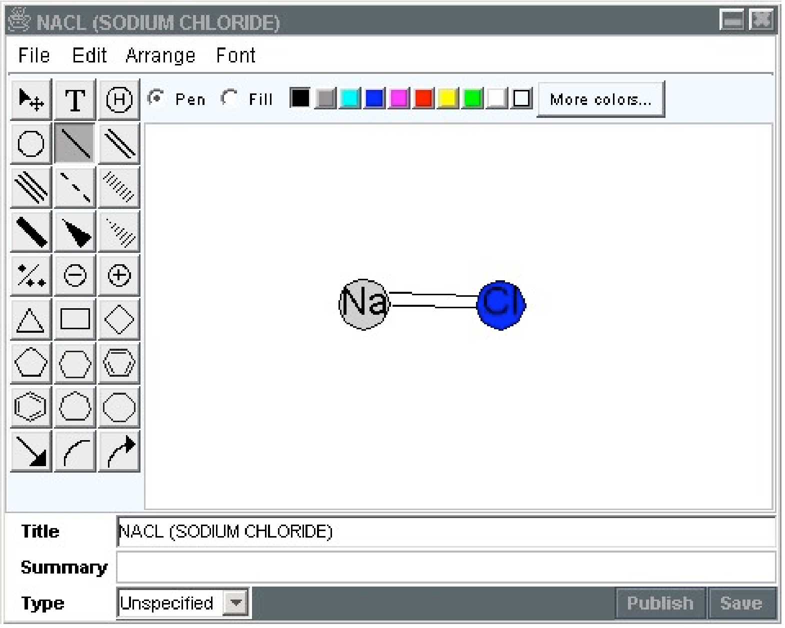
Hydrogen
H 1 (1.00794)

Figure 2. Large and small periodic table reference tools.

Tool Use Example 1: Irina and Caitlin

Lab 2 of the Solubility module, called "Types of Solutions," is designed to help students develop and understanding of aqueous solutions: electrolytes and nonelectrolytes. To begin, students are asked to draw, at the nanoscopic level, water as a liquid and sodium chloride as a solid. On their computer, Irina and Caitlin log in to ChemSense using their "group2" account, and build on their Group 2 root item using the studio drawing tool (see Figure 3). The drawing tool consists of a toolbar of shapes (Figure 3, left), a canvas drawing area (Figure 3, right), various color tools for the outline and fill color of shapes (Figure 3, top), menus with options for duplicating, moving, layering, and grouping selected shapes, and multiple levels of undo/redo.

Using the element chooser in the toolbar (the small circled "H"), they bring up a small periodic table. They select "Na", place it on the canvas, and do the same for "Cl". They then select both elements on the canvas, and use the Font menu to enlarge the text. Finally they use the single line (bond) in the toolbar to draw two lines between the elements.

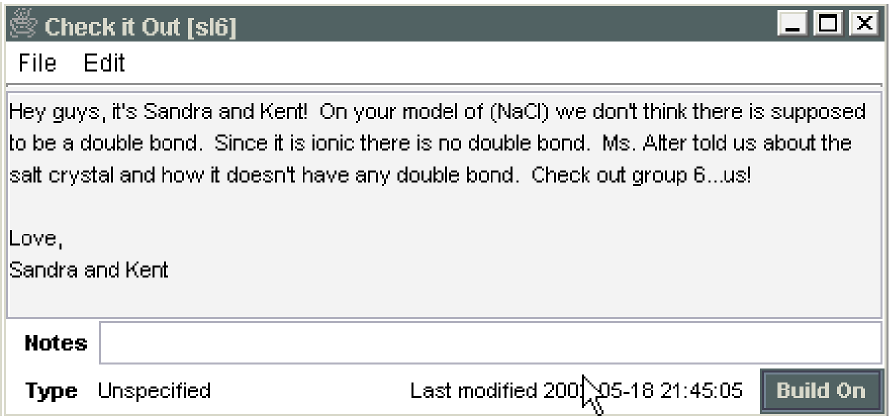


Title NACL (SODIUM CHLORIDE)
Summary
Type Unspecified

Figure 3. Editing a drawing: Irina and Caitlin's initial representation of sodium chloride.

Irina and Caitlin move on to draw water, and then to the next task of creating an animation showing what they think happens at a nanoscopic level over time as sodium chloride is added to water. As they work, they notice that a new item has appeared, indented, below their drawing of sodium chloride. The item is a text note from group 6, Sandra and Kent. Irina double-clicks on the note to view it (see Figure 6). The text tool is a simple word processor for unformatted text. It supports basic features like cut, copy, and paste, in addition to the standard import and export functions of all ChemSense tools. The background of the note is light blue, indicating that the text is not editable by Irina and Caitlin.

Sandra and Kent write that they don't think there is supposed to be a double bond in Irina and Caitlin's drawing of NaCl, because NaCl is ionic and their teacher told them that it doesn't have a double bond. They also invite Irina and Caitlin to look at their work. After reading the note, Irina and Catarina browse to find the work of group 6. They find Sandra and Kent's water molecule, but can't find their sodium chloride drawing. They build on group 6's water molecule with a text note thanking them for their advice, and asking them where their sodium chloride is so that they can comment on it (see Figure 5). Later, Irina and Caitlin edit their drawing of NaCl to remove the extra bond.



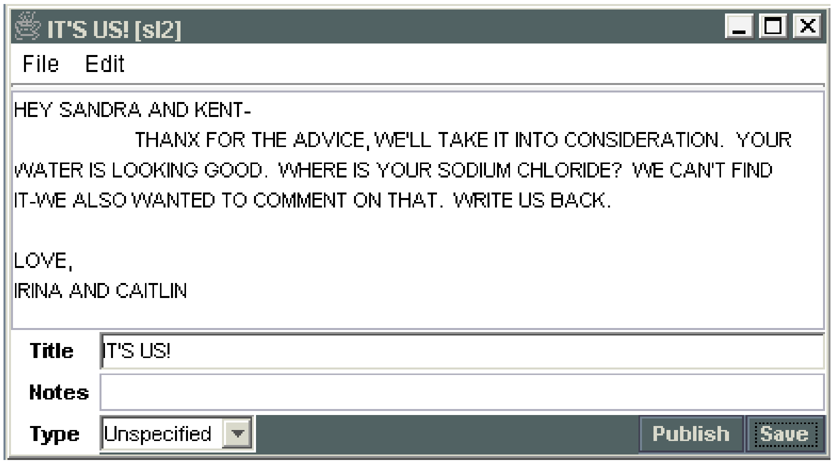
Hey guys, it's Sandra and Kent! On your model of (NaCl) we don't think there is supposed to be a double bond. Since it is ionic there is no double bond. Ms. Alter told us about the salt crystal and how it doesn't have any double bond. Check out group 6...us!

Love,
Sandra and Kent

Type Unspecified

Last modified 2001-05-18 21:45:05

Figure 4. Viewing a note: Group 6's review of Irina and Caitlin's drawing of sodium chloride.



HEY SANDRA AND KENT-
THANX FOR THE ADVICE, WE'LL TAKE IT INTO CONSIDERATION. YOUR WATER IS LOOKING GOOD. WHERE IS YOUR SODIUM CHLORIDE? WE CAN'T FIND IT-WE ALSO WANTED TO COMMENT ON THAT. WRITE US BACK.

LOVE,
IRINA AND CAITLIN

Title IT'S US!

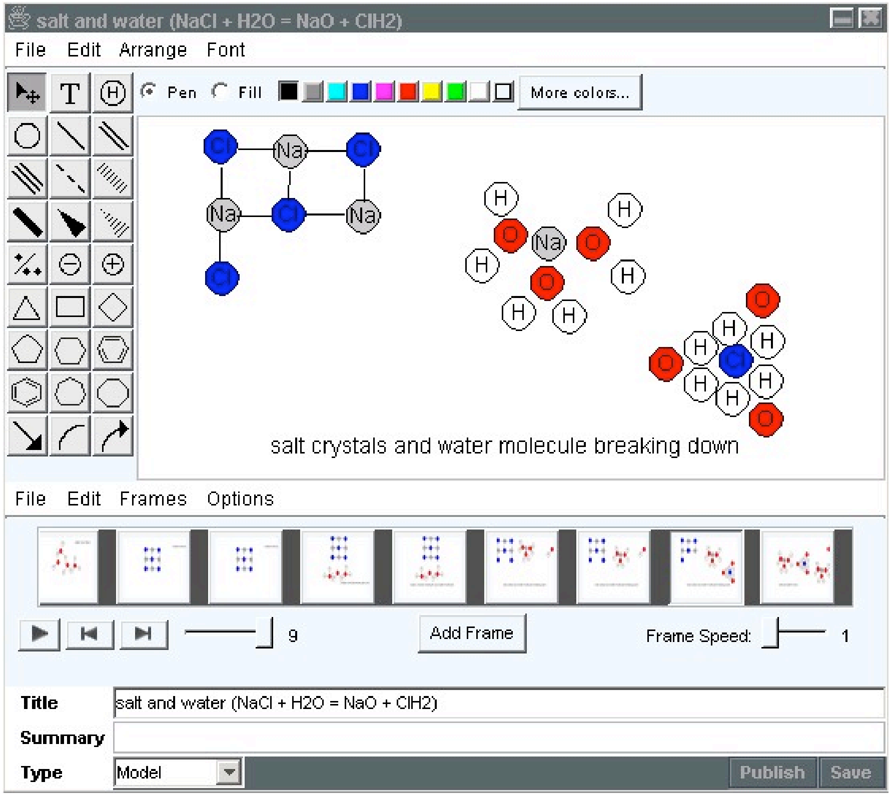
Type Unspecified

Figure 5. Editing a note: Irina and Caitlin's response to Group 6.

Irina and Caitlin turn back to the animation of what happens when sodium chloride is added to water. They build on their Group 2 root item using the animation tool (see Figure 6). This tools allows them to create a sequence of drawings (i.e., a storyboard) as separate frames of an animation. The top part of the animator window contains the current frame (a drawing). The bottom part of the window contains the animator controls. The controls consist of a filmstrip to interact with the frames, sliders and buttons (immediately below the filmstrip) to step through, play, and add frames, and a duration slider to specify the amount of time spent on the selected frame. Animations can be exported in Quicktime format for use in other applications.

Irina and Caitlin draw their representation of a sodium chloride crystal on the left, and molecules of water on the right. Over 10 frames, they slowly show the salt crystals and water molecules breaking down and mixing. They spend a lot of time planning and questioning the correct sequence of actions from frame to frame, and use the text tool to annotate each frame of the animation to describe what they think is happening. In the first frame (not shown), they use the text tool to write a chemical equation at the top that shows the solution being made: $NaCl + H_2O = NaO + ClH_2$. The text tool parses the text they enter to properly display the subscripts and superscripts of their formula. As the teacher passes by their lab station, she watches their animation and comments on several misconceptions that it reveals.

Irina and Caitlin finish the lab by answering questions about the characteristics of solutions, making solutions of sodium chloride at different concentrations, making predictions about conductivity and testing the solutions using a conductivity tester, and repeating this test with sugar solutions and four additional solutions of their choice. Finally, they are asked to look at two other groups' animations, predictions and results and remark on differences from their own.



salt and water (NaCl + H2O = NaO + ClH2)

● Pen ○ Fill

9

Frame Speed: 1

Title: salt and water (NaCl + H2O = NaO + ClH2)

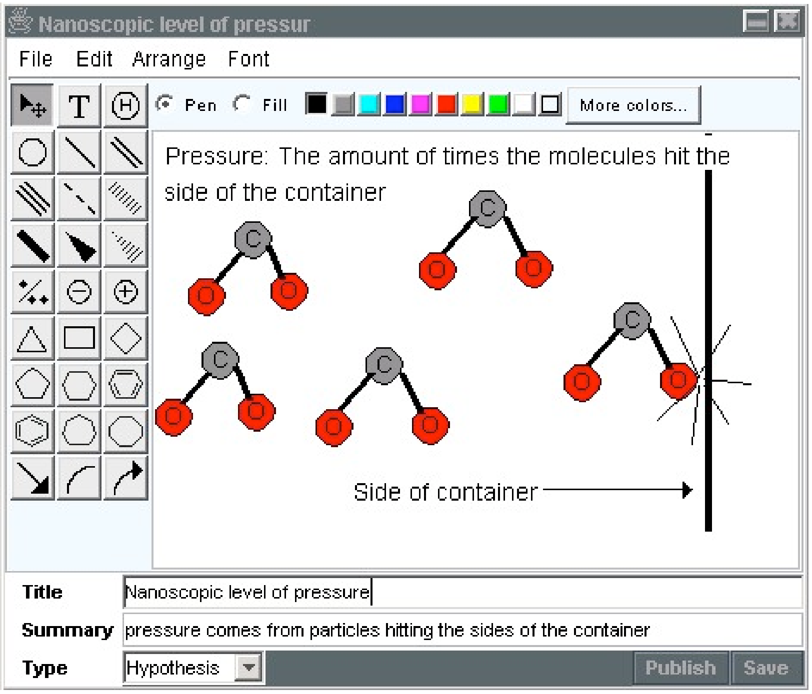
Summary:

Type: Model

Figure 6. Editing an animation: A frame from Irina and Caitlin's animation of what happens when salt and water are mixed together to make a solution.

Tool Use Example 2: Caleb and Emil

Lab 5 of the Solubility module, called "The Effect of Pressure on Solubility," is designed to help students develop and understanding of pressure and demonstrate the effect of pressure on the solubility of a gas dissolved in a liquid. Early on, students are asked to use pictures and words to explain their understanding of equilibrium and pressure. Caleb and Emil are logged in via their "group17" account, and build on their Lab 6 note using the studio drawing tool (see Figure 7). They use the text tool to annotate their drawing to emphasize that they think pressure comes from particles hitting the sides of the container.



Pressure: The amount of times the molecules hit the side of the container

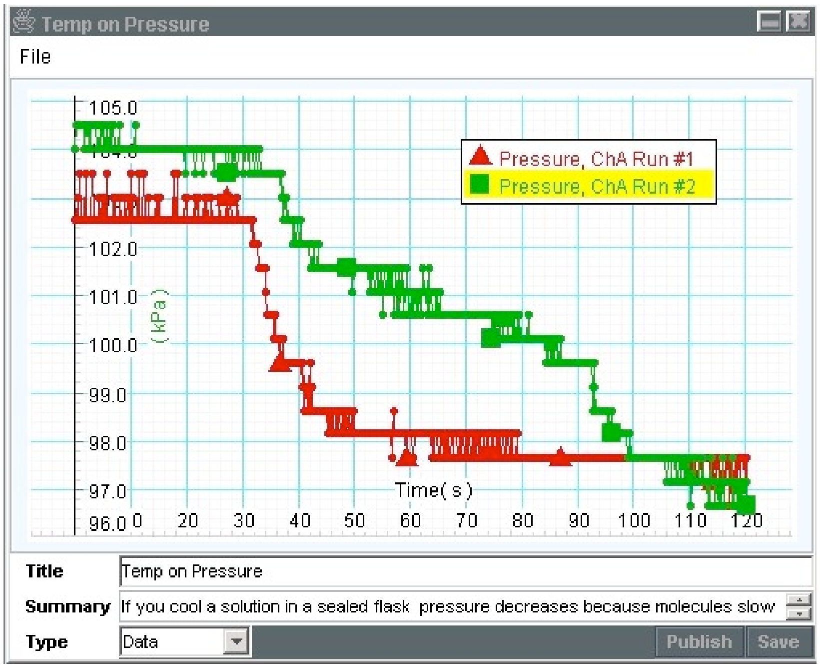
Title Nanoscopic level of pressure

Summary pressure comes from particles hitting the sides of the container

Type Hypothesis

Figure 7. Editing a drawing: Caleb and Emil's hypothesis of what pressure is.

Caleb and Emil gather their lab materials and practice using the PASCO pressure sensor to measure pressure in a syringe as they change the volume, and then to measure the pressure of carbonated water in a sealed container. Next, they make predictions about the effect of temperature on pressure, in particular, what will happen to pressure if you cool a solution in a sealed flask. They create a note with their prediction that "If you cool a solution in a sealed flask the pressure would decrease because the molecules are moving slower than before." They run their experiment using de-ionized water in a sealed flask in an ice bath, measuring the pressure in the flask with a PASCO pressure sensor. The data from the sensor is graphed in real time in PASCO's Data Studio software. Caleb exports the graph image from PASCO and then imports the image into ChemSense so he can share his data with others in the environment (see Figure 8). Like all ChemSense items, this image will be stored on the ChemSense server, so that others can access it when they log in.



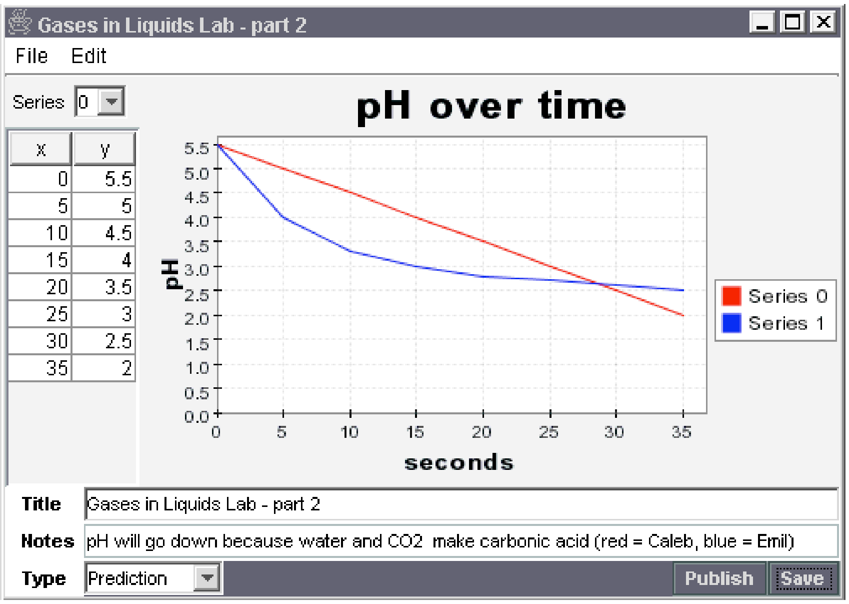
Title Temp on Pressure

Summary If you cool a solution in a sealed flask pressure decreases because molecules slow

Type Data

Figure 8. Importing an image: Caleb and Emil's pressure lab graph exported from PASCO and imported into ChemSense.

Caleb and Emil could have also used the ChemSense graphing tool[4] to plot and share their predictions before running a lab, or to view and manipulate data entered by hand or imported from other applications (see Figure 9). For example, Lab 3, "Gases in Liquids," asks students to create a solution of carbon dioxide in water, predict what will happen at the nanoscopic level when carbon dioxide is bubbled through water, and predict how the pH of the solution will change as the CO_2 combines with H_20 to form carbonic acid. Caleb and Emil did not graph their predictions (even on paper) for this lab, but the graph in Figure 9 shows possible graphs they *might* have drawn based on their written prediction that the pH of the solution would go down.[5] The graph data table (Figure 8, left) shows the X-Y coordinates (which could be entered by hand from data or as a prediction) of a selected series. The graph (Figure 9, center) plots one or more series of data as specified in the data table. Students can edit, append, insert, or delete X-Y values in a series, and add or delete a series. The axes and graph labels can also be modified via the tool's Edit menu. Graphs can be exported as tab-delimited files of the X-Y data and JPEG images for use in other applications.



x	y
0	5.5
5	5
10	4.5
15	4
20	3.5
25	3
30	2.5
35	2

Title Gases in Liquids Lab - part 2

Notes pH will go down because water and CO2 make carbonic acid (red = Caleb, blue = Emil)

Type Prediction

Figure 9. Editing a graph: How students could predict or view data in the ChemSense KBE.

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[4] At the time that Caleb and Emil used ChemSense (December, 2000), the graphing tool had not yet been implemented.

[5] This example is fabricated for illustration purposes only; it is the only example in this paper that is not actual student work.

SUMMARY OF RESEARCH FINDINGS

ChemSense has been designed and improved through a series of baseline and design studies (Schank et. al, 2000) and most recently through classroom use at a California high school and at the University of Michigan. A variety of qualitative and quantitative methods have been used to evaluate its impact, including pre and post student interviews, video analysis, and scoring of pretests, posttests, retention tests, and representations created by students. Scoring was done with rubrics designed by our team to measure representational competence and chemical understanding for each of the five chemical dimensions. For example, the representational competence rubric contains five levels ranging from “novice” to “expert”: (1) representation as depiction; (2) early symbolic skills; (3) syntactic use of formal representation; (4) semantic, social use of formal representations; and (5) reflective, rhetorical use of representation. Each of the chemical understanding rubrics has a similar five-level structure, and each focuses on different aspects of students' chemistry content and process knowledge. ChemSense was also used and evaluated by high school chemistry teachers in a Texas A&M summer workshop. Below is a summarize of the main findings from our classroom studies and teacher evaluations.

Student Learning

Working with 42 high school students using the Solubility curriculum module in December 2000, we found that students who created more drawings and animations in ChemSense over a 3-week period showed greater representational competence (ability to create and analyze representations) and deeper understanding of geometry-related aspects of chemical phenomena in their animations. Specifically, there was a significant, positive correlation between the number of drawings and animations created in ChemSense and the quality of the animations produced, as scored by raters using our chemical geometry and representational competence rubrics ($p<.05$). Students using ChemSense also showed significant improvement in representational competence and in their understanding of connectivity and geometry from pre- to posttest ($p<.05$). These findings suggest that the use of ChemSense as a representation “creation” tool facilitates representational ability and chemical understanding of underlying, nanoscopic mechanisms.

Analysis of videotapes of two high school groups working in the ChemSense environment shows that use of the tools requires students to think carefully through more specific aspects of chemical phenomena to which they might not otherwise attend, such as the number of molecules involved in a reaction, the particular bonds created in the reaction, the bond angles, or the sequence of steps in a reaction. Throughout the collaborative sessions that were videotaped, students used the representations to both develop and reveal their understandings of chemical phenomena.

Also, the high school students who started out with the most limited representational competence demonstrated the greatest improvement in representational competence over time. Specifically, there was a significant, negative correlation between pretest scores and gain (posttest minus pretest) scores ($p<.05$). Since the biggest gain in representational ability was made by those students who started with minimal representational ability, ChemSense may be an effective way to level the playing field between students by providing all students, regardless of their initial representational competence or attunements, with an effective way to generate and communicate chemical ideas.

In another study in November 2000, 25 University of Michigan undergraduate chemistry students worked with ChemSense tools in representing multi-step, organic chemical reactions. Preliminary quantitative findings show a positive correlation between the use of ChemSense and deeper chemical understanding. Video analysis revealed that in the process of planning (storyboarding) animations, students were speaking with each other about the stages of reactions in a more detailed way than they might normally, precisely because they needed to consider a greater level of detail. In other words, students arrived at a shared understanding of the chemical content through their planning and discussion of animations. These promising findings suggest that further, extended investigation is needed to fully understand the extent to which the ChemSense KBE promotes understanding of college-level curriculum.

The main difficulty observed with the technology was related to the lack of integration between the ChemSense KBE and PASCO. Students had to learn and coordinate two separate applications, and explicitly export data from PASCO and import it into the ChemSense KBE to share and discuss it with others. From a technical perspective, integration is difficult because PASCO products do not allow for real-time display of data directly in the ChemSense KBE; PASCO products are proprietary and require a separate DataStudio application for data display. A proposed a solution to this problem is outlined in the Implications section below.

Teacher Evaluation

During the course of these studies, the high school teachers seemed unsure about how to interact with students using ChemSense. They had positive impressions of the tool and were “amazed how focused the students were” (Larson, 2001), but they were unclear on how to assess or support their students' work. The teachers also noted that it was difficult for students to transfer their prior understanding of, and approach to, chemistry into the computer-mediated environment, and were challenged by the process of constructing their own understanding. The teachers wanted to both model and guide the students in this process but had an insufficient repertoire of strategies to help students pursue productive leads in their thinking. It is important to note that the teachers involved in these studies were not given any formal training on ChemSense, and were able to rely on the research team to answer student questions about ChemSense and the Solubility lab activities. It is possible this may have reduced the teachers' feelings of ownership and engagement in the use of ChemSense in their classrooms.

Professional development around ChemSense—including training and generation or adaptation of activities by teachers—can help mitigate some of these issues. In the summer of 2001, 16 teachers at a Texas A&M Science Teaching and Learning Center Teacher Workshop, "Structure and Properties of Matter and Chemical Reactions: Molecular Visualization," used ChemSense and three other chemistry visualization packages—RasMol, Chime, and ISIS/Draw—over a period of 3 weeks to create molecular visualizations. On a anonymous survey given after the workshop, which asked the teachers to evaluate the tools they used in the workshop, the teachers gave quite favorable evaluations of ChemSense (see Table 2). They liked ChemSense, thought it was easy to use (some thought it was the easiest of the packages they used), and felt it helped them—and would help their students—visualize chemical concepts. Indeed, no teacher disagreed with these statements, and most strongly agreed. They also suggested a few new features, including the ability to rotate molecules and support for 3D rendering. Ten of the teachers in the workshop requested their own set of ChemSense accounts for use with their students. Typical (anonymous) comments included:

> "I've been waiting to see a program like this for a long time that is easy to use and available to everyone (after its hopeful commercial availability of course). It is a wonderful tool in teaching visualizations of molecular processes."

> "I can't help but feel that the result's of this program will really help students' understanding of many concepts. I believe a good way to assess the impact of the program is to teach them how to use the program—I believe it is that simple; most general chem students could learn to use it—then have them construct their own animations on a different problem. If the tool were used from the beginning of a semester so that students build on previously constructed knowledge, it could be a great teaching tool!"

> "I found Chemsense the easiest of the programs to use. It seemed to be a more logical way to put in the items that you wanted for your animations. It was also interesting to build the frames and put in the changes and change the time of the frames to match what your mind was telling you should really happen. I felt that putting all of the information into a sequencing pattern helped me see the event and understand how the molecules were behaving in the reaction."

The teachers in the workshop also generated many ideas about how they might use ChemSense with their students (see Table 3). Although the topic content varied, many of these activity ideas involved student generation of animation, peer review, and the generation of presentations for classmates, middle school students, and/or future classes.

Table 2. Descriptive statistics for anonymous teacher evaluations (N=14) of ChemSense.

Responses were marked on a scale from 1 (strongly agree) to 5 (strongly disagree).

Evaluation survey question for ChemSense	Mean	SD	Mode	Max
I like the program.	1.5	.50	1	2
The program helps me visualize chemical concepts readily.	1.5	.51	1	2
The program was easy to use.	1.93	.61	2	3
The instructions were clear, understandable, and easy to follow.	1.79	.58	2	3
This program will help my students better visualize chemical concepts.	1.43	.64	1	3

Table 3. Activity ideas from teachers using ChemSense (from the anonymous survey).

"If I could get students to understand, say, Lewis dot structures of elements, then when introducing bonding and bonding patterns, I would ask them to show me through an animation, how the atoms rearrange, with proper stoichiometry, to form compounds. It would be interesting to see what they would do with moving electrons around to satisfy the octet rule. I think the student would truly find it amazing to "see" electrons rearranging to form bonds (and possibly the need for double or triple bonds) to see the octet rule in action."
"After showing students how the program is used, I would assign groups to create animations of the various types of reactions (oxidation-reduction, combination, decomposition, displacement, metathesis) which would be presented in front of the class. Student animations could then be critiqued by their peers and would segue into a more formal introduction of the chemistry behind the reaction by the instructor."
"For an redox reactions, we might work through several examples on the chalk board. Then, I might ask students to make an animation showing the movement of electrons in one of the reactions. We could review the work as a class, then make changes as required. The good thing about using Chemsense in an exercise like this is that it is so easy to make any changes necessary."
"I think that this program would be a good modeling tool for students to visualize molecules they have drawn on paper. I would like to develop plans for students to devise their own animations to portray basic chemical principles suitable for presentation to middle school students or to their classmates: the students would become the instructors with their tools."
"At the beginning of the year, have the students use this to show the law of conservation of matter during a chemical change. It can also show that not all particles in a system undergo a change. I would, after modeling how to use the program, have each of them build an animation using this to show not only the Law of Conservation of mass, but to show the molecular representations of the 5 types of reactions normally covered in a high school chemistry class, stoichiometry, gas laws, and acid/base theories."

IMPLICATIONS AND FUTURE WORK

Research to date indicates ChemSense's affordances as a representation creation and manipulation environment and highlights its potential to foster students' ability to use representations in expressing and understanding chemical ideas. These findings also highlight areas for improvement and further investigation. First, the high school studies thus far have focused primarily on one of the five chemical dimensions—geometry—as well as representational competence. We are encouraged that ChemSense will be a powerful tool to foster understanding around the other four chemical dimensions (connectivity, aggregation, state, and concentration). To investigate how ChemSense supports students' understanding of the additional chemical dimensions we need to extend the current set of curricular activities. For example, the "connectivity" dimension focuses on the making and breaking of chemical bonds. To investigate how well ChemSense promotes understanding of how and why bonds form, a bond-intensive curricular module, such as acid-base reactions, could be developed. Extension of the ChemSense tool set may also be needed to support new curricular modules.

Second, the studies thus far have been limited to 4 weeks or less. Although these studies have shown positive learning outcomes, longer-term studies are needed to fully understand the impact of ChemSense and how students' chemical understanding and representational competence change over time. To this end, future teacher-developed ChemSense curricula would take on a more holistic approach, one that is more integrated with a teacher's semester-long curriculum rather than being a single "unit" that is implanted in the normal high school or college chemistry curriculum.

Third, student learning can be enhanced by the greater use of formative assessment within ChemSense, as well as greater support for teachers in their use of the ChemSense tools and development of ChemSense-based curriculum. In the studies to date, we have used limited formative assessment, often employing "teachable moments" during the daily use of ChemSense and relying on summative assessments to measure student learning. Facilitation of student-teacher interactions to support learning needs to be built into our ChemSense technology and activities. To do so, teachers need formal training on how, when, and why to use ChemSense, and to develop a structured way to support teachers in their use of ChemSense. As the teachers become more familiar with the tools, we can help them adapt and develop particular strategies—for use in both ChemSense-mediated and face-to-face interactions with students—to scaffold students' understanding of chemical phenomena. Specifically, the ChemSense project will focus on strategies such as prompting, questioning, explaining, and otherwise helping attune students to the resources (linguistic, physical, and conceptual) that can lead them to greater precision and elaboration in their understanding. Administration and summarization tools will also be added to the environment to allow teachers to aggregate knowledge-building data (number and types of contributions to the KBE) from individual students and across students. The software will also be enhanced to allow teachers to offer private commentary on student work, to refer students to other text or representations in the environment relevant to their work, and to score students' products and presentations.

Finally, recent advances in handheld technology could enable students to collect and discuss data more flexibly and analyze it in real time in the ChemSense environment. For example, using new sensor interfaces and Palm software, students could connect probes to a Palm handheld and collect data in a mobile fashion (graphed on the handheld display) or at their stations for real-time display in the ChemSense KBE. Data collected away from the lab station (e.g., outdoors) could also be saved as tab-delimited files and imported into ChemSense later for discussion.

In sum, our future activities will be to work with teachers to develop additional ChemSense-based representational activities and assessments that build on and enhance their existing curricula, to refine the ChemSense tools to support these activities, and to implement ChemSense in the classroom over an entire semester. This integrated, sustained use would support deeper research on teachers' learning processes and the impact of inquiry and representational use on student learning and classroom practice.

ACKNOWLEDGMENTS

The authors are very grateful to Brian Coppola and Judy Larson, who helped us design ChemSense and let us study its impact in their classrooms, and to Vera Michalchik, Anders Rosenquist, Patty Kreikemeier, and Fumiko Allen for their extensive work on study design, data collection, and analysis. This material is based upon work supported by the National Science Foundation under Grant No. 9814653. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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