To appear in J. Gilbert, M. Nakhleh, & M. Reiner (eds.), Visualization: Theory and practice in science education. New York: Springer.

Representational Resources for Constructing Shared Understandings in the High School Chemistry Classroom

Vera Michalchik, Anders Rosenquist, Robert Kozma, Patty Kreikemeier, and Patricia Schank

Center for Technology in Learning, SRI International

Brian Coppola

Department of Chemistry, University of Michigan

Address correspondence to:

Vera Michalchik

SRI International

333 Ravenswood Ave.

Menlo Park, CA 94305

vera.michalchik@sri.com

Voice: 650-859-4176

Fax: 650-859-4605

ABSTRACT

This chapter reports on the use of representational resources within a computer-based environment, called *ChemSense*, to support high school chemistry students' representational practices and their understanding of key chemical concepts. In designing *ChemSense*, we hypothesized that it would provide students with symbolic resources they could use to jointly construct representations of observable physical phenomena and to explain these phenomena in terms of underlying chemical entities and processes. This study examines the role that these representational resources play in supporting students' representational practices and their emerging chemical understanding. To elucidate how *ChemSense* supports the development of representational practice and chemical understanding, we provide an analysis of students' conversation while they use *ChemSense* in the laboratory. Our findings indicate that students use *ChemSense* to construct their shared understanding of chemical phenomena in a common representational space. Their representations serve as key symbolic resources in students' collaborative efforts to generate coherent explanations of the phenomena they are investigating. On the basis of our analysis we conclude that when using representational resources as part of collaborative investigations, the nature of students' conversation becomes more 'chemical' and students deepen their understanding of the molecular nature of physical phenomena that have, as a result, become chemical.

INTRODUCTION

In an important sense, chemistry is the practice of using representations to understand molecular phenomena (Hoffmann & Laszlo, 1991). In the history and current practice of chemistry, understanding molecular properties and processes has been a challenge, in large part because molecules and their properties are not available to direct perception. Consequently, chemists have designed a range of representational systems that mediate between something that they cannot see and something that they can. Some representations—such as formulas, equations, and structural diagrams—are generated by the scientists themselves to conceptualize, plan, and interpret the results of the research they are conducting. Some representations are generated by research instruments, such as spectrographs and chromatographs, which give physical manifestation to certain aspects of molecules, such as the mass of their structural components. And some representations, specifically graphical molecular models, are generated by scientists using computer technology. However they are created, making meaning with representations is a core practice of the chemistry community and is essential to the understanding that chemists have of their domain. In an observational study of chemists in their laboratories, Kozma, Chin, Russell, and Marx (2000) found that chemists used a variety of representations together to construct an understanding of the chemical phenomena they investigated in their experiments. Chemists used structural diagrams to describe the composition and geometry of the compounds that they were trying to synthesize. They used diagrams and chemical equations to reason about the reaction mechanisms needed to transform reagents into products and the physical processes that would support these transformations. Chemists analyzed various instrumental displays and printouts to verify the composition and structure of the compounds that they were trying to synthesize. As they worked together to understand the results of their investigations, chemists made references to specific features of the printouts (e.g., peaks on nuclear magnetic resonance or mass spectra) as warrants for claims that the desired products were obtained. In the course of their collaborative work, they both draw on and contribute to the shared understanding of their domain as it is encoded in their representational systems. In this regard, the meaning of the symbolic representations and the physical phenomena to which they refer are mutually constitutive and reify one another (Roth, in press). That is, the meaning of the chemical representations emerges out of chemists' interaction with the specific phenomena in the laboratory, and at the same time the laboratory phenomena become socially constructed as "chemical" through the use of these representations. However, the deep understanding and rich representational practices of chemists stand in sharp contrast to those of chemistry students. In Kozma's (2000a) observations of university students enrolled in an organic chemistry course, there was little use of representations during their wet-lab experiments. The primary interaction among student lab partners was focused on setting up equipment, troubleshooting procedural problems, and interacting with the physical properties of the reagents they were using (e.g., was their crystalline product washed enough or dry enough). Unlike the discourse of chemists, Kozma observed very little discussion among students about the molecular properties of the compounds they were synthesizing or the reaction mechanism that might be taking place during their experiments. The poor representational practices of students in the laboratory observed by Kozma correspond to results from other studies (Hinton & Nakhleh, 1999; Gabel, 1998; Nakhleh, 2002; Kozma & Russell, 1997). Too often, students do not relate phenomena they perceive in the laboratory (reagents precipitating or changing color) to underlying entities and processes (bonds forming or breaking between atoms) (Bunce & Gabel, 2002; Hinton & Nakhleh, 1999). At the same time, students are able to solve chemical equations but do not know how these connect to the aperceptual chemical phenomena they represent (Dori, Barak, & Adir, 2003; Hinton & Nakhleh, 1999; Nakhleh, Lowrey, & Mitchell, 1996). As a result, the representations and related practices that are so meaningful and useful to chemists are relatively meaningless to students, and they are not able to use these to develop a chemical understanding. As Krajcik (1991) points out, although students frequently become good at manipulating chemical symbols, they often treat them as mathematical puzzles without possessing an understanding of the chemistry that corresponds to these symbols.

The root cause of this problem, we believe, is the way representations are typically used in chemistry courses. Standard chemistry textbooks are filled with problems at the end of each chapter for which students manipulate various representations to get the correct answer, but these problems do not correspond to experienced laboratory phenomena. Or as part of their laboratory report, students are asked to compute the concentration of reagents at different temperatures, but their procedures are mechanical and not part of authentic laboratory investigation. The lack of connection between representations and their meaning is due to the disconnection between representational use and the practice of laboratory chemistry. In the design experiment reported in this paper, we address this problem. We report on the use of representational resources in a high school chemistry laboratory that were designed specifically to support the development of students' skills in the use of representations in a laboratory context and the development of their understanding of the chemical nature of the phenomena that they investigate. In this report, we describe the computer-based environment that we designed, called *ChemSense*, and we list the theory-based hypotheses embedded in the particulars of its design. We examine the impact of the use of the environment on the representational competence and chemical understanding of high school chemistry students. We also analyze the conversation of students while they use

ChemSense in the laboratory to elucidate the mechanisms by which *ChemSense* supports the development of representational practice and chemical understanding.

Theoretical Perspective

The theoretical perspective we take in our research and design is situative. In brief, situative theory posits that the concrete details of settings shape social and psychological processes of participants through the constraints and affordances of the material, informational, and social systems that characterize the setting (Greeno, 1998; Roth, 1998, 2001). *Constraints* are those characteristics that structure and to some extent limit the range of possible actions within the system. *Affordances* are those resources in the environment and enabling characteristics of the person or group that increase the range of possible actions in certain ways. Situative analyses emphasize communication and reasoning about and with physical objects (tools, artifacts, etc.) and events in the setting of an activity. *Representations* serve a special function within the situative theoretical perspective since representations do not have meaning in themselves. Rather, meanings are characterized as relationships between the representations and the objects and events to which the representations refer but that are not present. As such, representations—such as written or drawn symbols, iconic gestures or diagrams, and spoken, gestured, written, or drawn indices—are not intended to be treated as objects themselves but as things that "stand for" or "refer to" other objects, representations, or situations. That is, the meanings of representations do not inhere in the qualities of the representations themselves but are derived as people interpret them, thereby constructing semiotic, "refers-to" relations between occurrences of the representation and entities or events that they designate. Creating these refers-to relationships is an important practice of a community and a source of their shared understanding. As people engage in activities in a community, they become "attuned" to the affordances and constraints of the material and symbolic resources of its various settings. Crucial to the function of any social system or community are the conventions of interpreting meanings of representations. Likewise, attunements to the constraints and affordances of these conventions are essential for an individual's emerging participation in the practices of a community. From a situative perspective, learning can be viewed largely as a progressive attunement to disciplinary ways of seeing and using representations within a community (Goodwin, 1995; Greeno & Hall, 1997; Stevens & Hall, 1998). Accordingly, recent efforts to examine science learning *as* participation in legitimate scientific activity—its particular discursive and behavioral forms, including experimentation and analysis—have focused increasingly on the characteristics and social use of scientific representations (Lemke, 1990; Roth, 1995). From the situative perspective, Greeno (1998) characterizes classrooms that are oriented to these practices as ones that encourage students to participate in activities that include the formulation and evaluation of conjectures, examples, applications, hypotheses, evidence, conclusions, and arguments—consequently promoting conceptual growth and skill acquisition in relation to these participatory activities. In such classrooms, discussions are organized to foster not only students' learning of the subject-matter domain but also their learning to participate in the discourse practices that organize the discussions. Students in these settings use representations to express their understanding of key concepts in the domain and, perhaps more importantly, to learn to use those representational systems in developing and sharing their understandings of questions, hypotheses, and arguments in the domain. Such student practice reflects recent thinking in pragmatics (e.g., Clark, 1996), ethnomethodology (e.g., Schegloff, 1992), linguistic anthropology (e.g., Hanks, 1999), and learning theory (Barron, 2003) that emphasizes the role of discursive representations and phenomenal objects as referential resources in establishing intersubjectivity and shared attention in the joint construction of meaning.

Using the situative perspective, we have designed a representational system—*ChemSense*—to support students' representational practices in the context of structured activities and laboratory investigations. The intent of our design is both to support student understanding of key chemical concepts and to develop their skills in using representations in this context.

Representational Technology and *ChemSense*

The *ChemSense* environment offers an ensemble of tools that enable students to create their own representations of chemical phenomena (Schank & Kozma, 2002). The basic premise of the *ChemSense* design is that these tools will be used within a social context of structured, collaborative investigations of physical phenomena in the wet lab. Students use the tools in *ChemSense* to construct their shared understanding of chemical phenomena in a common representational space and do this within a classroom and task context that includes physical lab equipment and data collection probeware. The environment has specific affordances and constraints designed to support and shape the representational practices and shared meaning making within an emerging student chemistry community in ways that are analogous to those of chemists. Figure 1 shows the basic layout of *ChemSense* as used in the study. The environment contains a set of tools—drawing, animation, graphing, and text tools—for creating and viewing representations and a threaded discussion section for peer review. The environment also includes a reference periodic table and a simple HTLM editor for creating Web-friendly lab reports. The tools within *ChemSense* are simple by design, containing only the primitive components necessary to construct a full array of chemical structures.

Several examples of student-generated items can be seen in Figure 1. In the center of the window is an animation that students created to show the process of sodium chloride (NaCl) dissolving in water. To create this animation, the students constructed individual frames that stepped through the breaking of ionic bonds between the Na^+ and Cl^- ions and the subsequent "hydration," or surrounding of the ions by the water molecules. To the right of the animation is the display of a dynamic graph that shows student-collected data on the change in the amount of dissolved oxygen in a solution. These data were collected at the lab bench through the use of probeware (developed by PASCO Scientific, Roseville, CA) and imported into the *ChemSense* environment. Other features and functions are shown in the figure, such as the navigation structure (left), periodic table (top right), and a student-created text entry in the threaded discussion that poses a question about solutions (top center).

In its use, *ChemSense* requires students to make critical design decisions while creating representations, and in this way it is designed to shape the way students think and talk about representations, physical phenomena, and underlying chemical entities and processes. To highlight this point, an example student activity will be discussed—the dissolving of salt (NaCl) in water. This activity was investigated by lab groups in this study and is analyzed in detail in later sections of the article. But for the moment we will use this example as a way to illustrate the use of the features and functions of *ChemSense*, as well as the rationale around which these features and functions were designed.

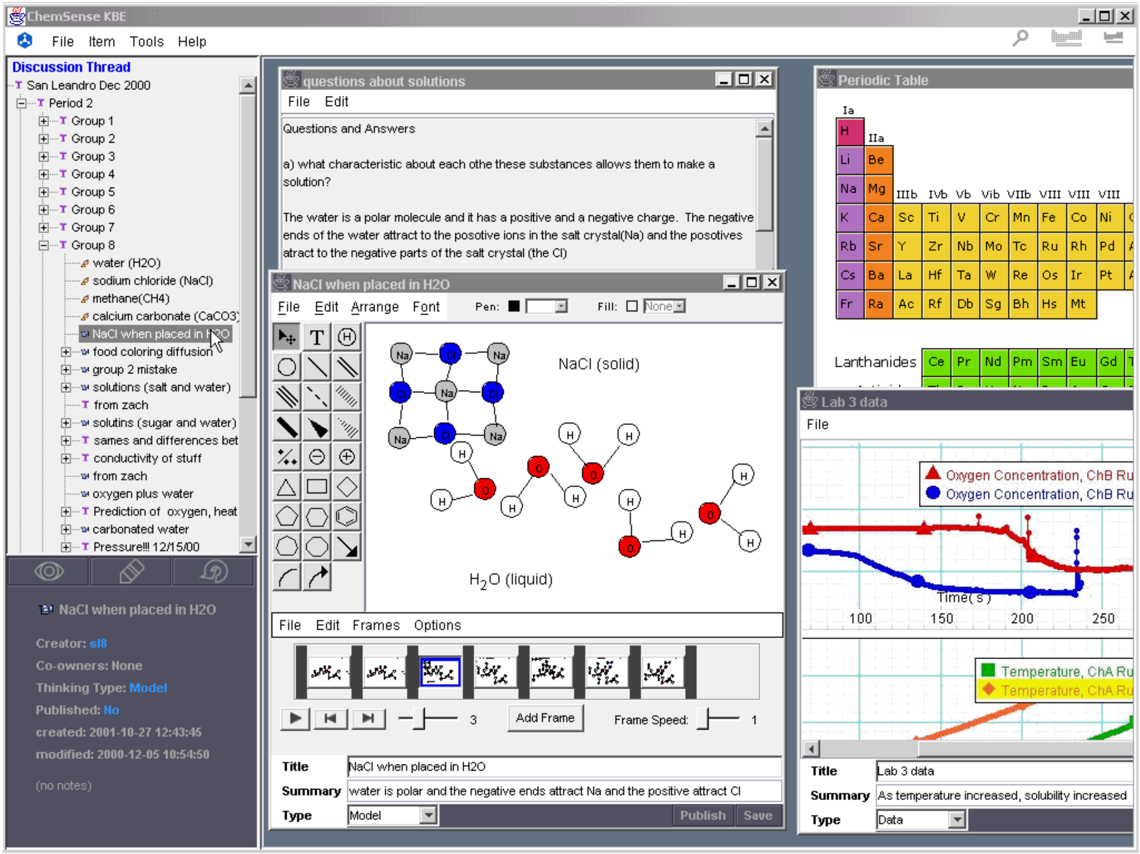


FIGURE 1. The *ChemSense* workspace, showing a sample high of school student work.

In this sample activity, students are asked to create a nanoscopic-level representation showing what happens when sodium chloride is dissolved in water. Since this dissolving process takes place over time, the students use the animation tool to build their representation of this dynamic process. Upon opening a new animation window, they are confronted with a set of design decisions regarding how to represent their understanding of the salt dissolving process. They are immediately confronted with a series of decisions: What does a water molecule look like? What is the structure of sodium chloride? What happens to the water and sodium chloride structures as they meet? A specific design decision in the development of *ChemSense* was *not* to provide a complete menu of preconstructed molecules so that students would be confronted with these very decisions.

As students begin creating, for example, a water molecule, they make choices from the animation tool palette (Figure 2) to create their representation. As seen in Figure 2, the palette contains only basic, elemental representational components such as atoms, bonds, and organic structures. The students use these basic building blocks to construct their representation as they negotiate a new set of decisions around the construction of the molecule: Which atoms are involved? How many are there of each kind? What type of bond exists between atoms? Which atoms are bonded to which? What are the spatial arrangements of the atoms? How do these arrangements change over time? As is the case of all molecular structures in *ChemSense*, a student cannot simply select a “water molecule” option and stamp out a set of H_2O molecules.[1]

[1] To avoid tedium, once the student designs one molecule, she can easily group the components of the molecule, copy them, and then stamp out multiple copies of her design.

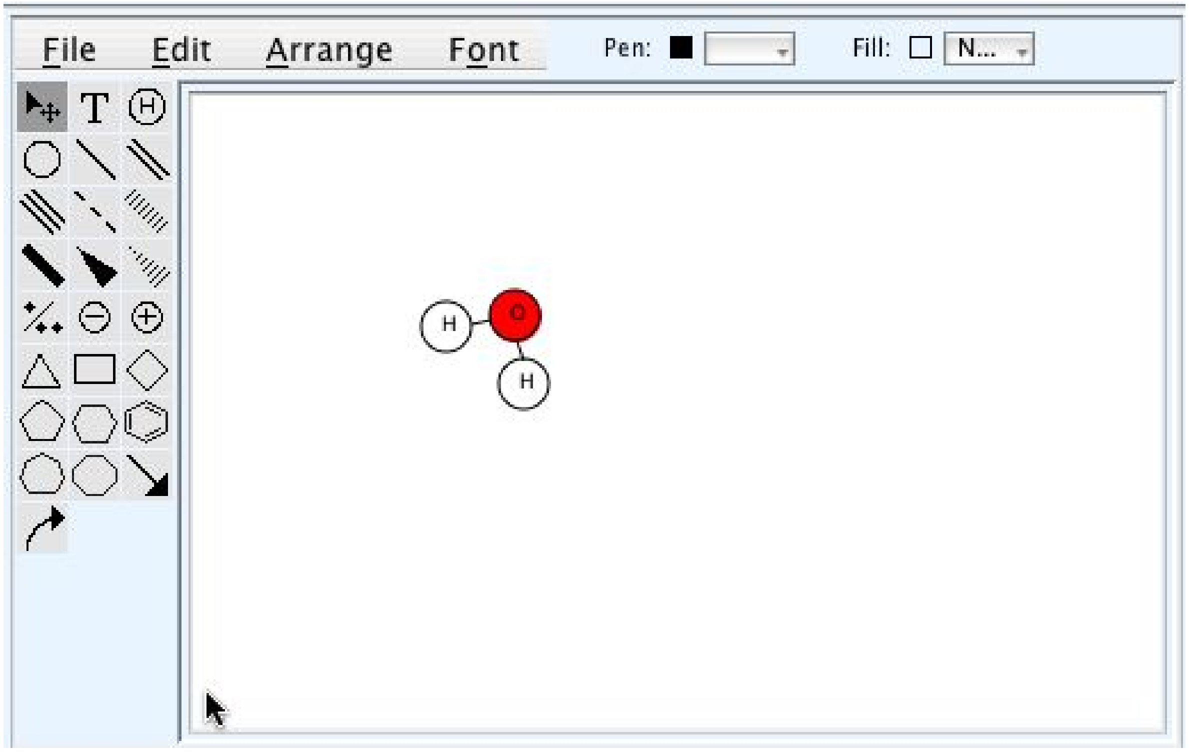


FIGURE 2. The *ChemSense* drawing tool palette. The palette (left) contains basic chemistry components—atoms, bonds, structures—that students use to create representations.

The *ChemSense* environment also gives students the means to coordinate nanoscopic representations with observable phenomena by using probeware.[2] This feature allows students to import graphical or tabular data directly into their representations from bench-top investigations and other inquiry-based activities (Krajcik, Blumenfeld, Marx, Bass, Fredericks, & Soloway, 1998; Roth & Bowen, 1999). For example, students collect wet-lab data such as temperature or dissolved oxygen content and import the data into *ChemSense*. They are then able to create and

[2] PASCO data collection tools, which students used in conjunction with *ChemSense* for this study, allow collection of real-time chemical data, such as temperature, pH, and dissolved oxygen, over a specified time period. Using a small "interface box" that is connected between the individual probes and the computer, data are collected directly into the computer, at which point they can be represented, analyzed, and imported into *ChemSense*.

run two representations—a nanoscopic-level representation showing the underlying process and a tool-generated representation showing the change in observable properties. The goal of using two representations that show parallel changes at the nanoscopic and physical levels is to get students to construct “refers to” relationships and to use representations at the nanoscale to explain the emergent properties of what they see on the lab bench. The empirical, data-generated representations (e.g., graphs) say more than the physical manifestations of chemical reactions on the lab bench (e.g., the salt dissolving in water) and allow chemistry students to think and talk about the nanoscopic entities and phenomena that account for the physical changes. Our intent is that data-generated representations will help students confirm or disconfirm what they *think* is going on at the nanoscopic level with what actually happens on the lab bench.

ChemSense is used in the context of specially designed curriculum units and investigative activities that scaffold student use of interconnected forms of visual and discursive representations and ask students to describe, explain, and argue about the chemical experiments they are conducting on the lab bench. In addition the “knowledge-building” function of the environment allows students to peer-review each other’s work through threaded discussion and commentary. For example, a teacher may include as part of an activity a section toward the end of a unit that asks students to “review the work of two other lab groups and ask two questions related to the chemistry in their representation.” As part of their “assignment,” each lab group is responsible for providing critical feedback on other students’ work. Used appropriately, this function further supports the possibility for students to collectively arrive at new understandings of scientific concepts by asking students to probe other students’ thinking (compare with Bell & Linn, 2000; Brown & Campione, 1996; Greeno, 1998; Kozma, 2000b; Linn, Bell, & Hsi, 1998; Pea, 1992, 1994; Scardamalia & Bereiter, 1994).

Together, the *ChemSense* tools and pedagogical activities are intended to help students bridge the gap between what they can see and the underlying processes that drive chemical reactions—to use representational practices to develop their chemical understanding. Our overall design hypothesis is that students' ability to readily generate representations at the nanoscopic level helps them move from simply depicting surface features of chemical phenomena to understanding chemical phenomena in terms of underlying molecular entities and processes. Consequently, our analysis of this learning process focuses on the role of *ChemSense* in enabling two important and interrelated lines of development: representational competence and chemical understanding.

Representational Competence

A major goal in our design of *ChemSense* is that while using various representations to negotiate a shared understanding of chemistry, students will become progressively attuned to a chemical way of using representations to analyze phenomena. "Representational competence" is a term we use to describe a set of skills and practices that allow a person to reflectively use a variety of representations, singly and together, to think about, communicate, and act on aperceptual physical entities and processes (see Kozma, 2000c). While those with little representational competence in a domain rely primarily on the surface features of representations to derive meaning (Chi, Feltovich, & Glaser, 1981; diSessa, Hammer, Sherin, & Kolpakowski, 1991; Kozma & Russell, 1997) or on the mechanical application of symbolic rules (Krajcik, 1991), those with more skill have come to use a variety of formal and informal representations together to explain a phenomenon, support a claim, solve a problem, or make a prediction within a community of practice (Amman & Knorr Cetina, 1990; Dunbar, 1997; Goodwin, 1995; Kozma & Russell, 1997; Kozma et al., 2000; Woolgar, 1990). For chemists, the act of using representations to successfully construct chemical understanding at once constitutes the meaningfulness of the representation and confirms the user's ability to participate in this representational, meaning-making activity (Kozma et al., 2000). One can neither understand chemistry without using representations nor use representations of the domain without some understanding of chemistry. These skill sets mutually evolve and constitute each other. Consequently, representational competence is the complement of chemical understanding, the first focusing on the activity of using representations and the second focusing on the resultant meaning construed from this activity.

To characterize this skill set, we propose a conceptual structure that organizes representational competence into characteristic patterns of representational use at five stages or levels (Table 1). This structure corresponds to a developmental trajectory that generally moves from the use of surface features to define phenomena, which is characteristic of novices within a domain, to the rhetorical use of representations, which is characteristic of expert behavior.

TABLE 1

Summary of Representational Competence Levels

Level	Description
Level 1: Representation as depiction	When asked to represent a physical phenomenon, the person generates representations of the phenomenon based only on its physical features. That is, the representation is an isomorphic, iconic depiction of the phenomenon at a point in time.
Level 2: Early symbolic skills	When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on its

	physical features but also includes some symbolic elements to accommodate the limitations of the medium (e.g., use of symbolic elements such as arrows to represent dynamic notions, such as time or motion or an observable cause, in a static medium, such as paper). The person may be familiar with a formal representational system, but its use is merely a literal reading of a representation's surface features without regard to syntax and semantics.
Level 3: Syntactic use of formal representations	When asked to represent a physical phenomenon, the person generates representations of the phenomenon based on both observed physical features and unobserved, underlying entities or processes (such as an unobserved cause), even though the representational system may be invented and idiosyncratic and the represented entities or processes may not be scientifically accurate. The person is able to use formal representations correctly but focuses on the syntax of use, rather than on the meaning of the representation. Similarly, the person makes connections across two different representations of the same phenomenon based only on syntactic rules or shared surface features, rather than the shared, underlying meaning of the different representations and their features.
Level 4: Semantic use of formal	When asked to represent a physical phenomenon, the person

representations	correctly uses a formal symbol system to represent underlying, nonobservable entities and processes. The person is able to use a formal representational system based on both syntactic rules and meaning, relative to some physical phenomenon that it represents. The person is able to make connections across two different representations or transform one representation to another based on the shared meaning of the different representations and their features. The person can provide a common underlying meaning for several kinds of superficially different representations and transform any given representation into an equivalent representation in another form. The person spontaneously uses representations to explain a phenomenon, solve a problem, or make a prediction.
Level 5: Reflective, rhetorical use of representations	When asked to explain a physical phenomenon, the person uses one or more representations to explain the relationship between physical properties and underlying entities and processes. The person can use specific features of the representation to warrant claims within a social, rhetorical context. He or she can select or construct the representation most appropriate for a particular situation and explain why that representation is more appropriate than another. The person is able to take the epistemological position that we are not able to experience certain phenomena directly and that

these can be understood only through their representations. Consequently, this understanding is open to interpretation, and confidence in an interpretation is increased to the extent that representations can be made to correspond to each other in important ways and that these arguments are compelling to others within the community.

We use this structure to analyze the extent to which the design features of *ChemSense* and the corollary laboratory activities and social discourse support students' emergent representational competence. For this study, we developed assessments that engage students in the use of representations to describe and explain chemical phenomena. They are paper-and-pencil assessments not used in a social context. Consequently, the assessment focuses primarily on levels 1-4. We have also developed sets of rubrics to code and analyze these assessments and other representational acts.

Chemical Understanding

A second goal in our design of *ChemSense* is that while constructing and using representations students will come to have a deeper understanding of laboratory phenomena in terms of underlying chemical concepts. A distinguishing characteristic between expert and novice use of chemical representations is that novices associate various representations by their common superficial features, whereas chemists associate them by their shared underlying, fundamental concepts (Kozma & Russell, 1997). The underlying, fundamental chemical concepts referred to in our analysis can be systematically organized to provide a comprehensive, nanoscopic-level framework that characterizes crucial aspects of chemical phenomena and constitutes a curriculum of sorts that we want students to understand as a result of using *ChemSense*.

To this end, we have developed five fundamental chemical dimensions or "themes"—connectivity, aggregation, geometry, concentration, and state—that correspond to basic curricular themes set out in the *AAAS Benchmarks* (AAAS, 1993) and cut across all traditional introductory chemical topics, such as acid-base reactivity, electrochemistry, solubility, kinetics, and thermodynamics. Although any given *ChemSense* activity may focus on a subset of the themes, taken together, the themes fully portray the molecular world imagined by chemists to account for observable phenomena. Each theme involves molecular arrangements or changes in structure that correspond to critical aspects of explaining chemical reactivity. A basic understanding of these substantive chemical themes will help the reader understand both the purposes of our design and the subsequent analyses of student discourse and learning.

Three of the representational themes—connectivity, geometry, and aggregation—relate primarily to structural issues. For example, the properties of water (e.g., liquid at room temperature, 100˚C boiling point, dipole moment, ability to solvate, high heat capacity) are related to the unique structural identity of water molecules (two hydrogen atoms and one oxygen atom with the H-O-H connectivity, arranged in a "bent" geometry) and the way they interact with other nanoscopic species (supramolecularity). Representing the visualization of structural changes taking place in chemical phenomena could involve changes in connectivity (bonds breaking and forming), changes in geometry (the spatial relationships between atoms in molecules and networks), and changes in aggregation (supramolecularity).

The other two representational themes—changes in state and concentration—describe the energy and motion of aggregations of molecules. These themes cover descriptions most commonly associated with the physical chemical attributes of thermodynamics (state) and reaction rates (concentration.) Below are short descriptions of the themes and then a discussion of the relationship between these themes and the design of the *ChemSense* environment.

Connectivity. Connectivity describes the connection between atoms within a particular molecular structure as a critical attribute of its chemical identity. These patterns of connectivity are often associated with certain perceptual qualities of a compound (group of molecules), such as predicting and explaining observed properties and/or reactivity (e.g., solubility in and/or reaction with water).

Geometry. Geometry centers on shape-related aspects of a molecule. There are two related aspects to molecular geometry. First are the static or fixed spatial relationships in molecular structure (average bond distances and bond angles). Second are the dynamic relationships that change over time (bond vibrations and rotations, and the more severe changes that accompany chemical reactions).

Aggregation. Aggregation refers to the emergent properties of a substance that arise from the spatial arrangement of many individual molecular entities, whether they are molecules, individual atoms, or ions. For example, aggregation forces determine why some salts dissolve in water and others do not, and why some chemical compounds mix while others do not.

State. State describes the energy relationships that exist within a set of molecules (one or more "bonded" or connected atoms) or individual elements (group of individual, "unbonded" or unconnected atoms). Applied heat, light, and the heat generated during mixing are the three most common sources of energy that influence changes in state. When molecules absorb or emit energy in the form of heat or light, the molecules undergo a change in state (e.g., "state of matter," such as going from liquid to solid; thermodynamic states more generally, such as water at 10˚C going to water at 50˚C). The average energy of a collection of molecules will determine the state in which a substance exists.

Concentration. Measures of concentration usually express the number of molecules per unit volume. When materials combine to undergo chemical reactions, large collections of molecules mix and collide with one another. Changes in concentration affect the number of collisions that take place—the higher the concentration, the greater the number of collisions and the greater the likelihood that a productive collision (i.e., some change occurs) will take place.

These five chemical themes guided the design of the *ChemSense* tools and directed development of the curriculum and assessments used in our work. We designed *ChemSense* so that students would make decisions related to these themes; the *ChemSense* tools specifically afford opportunities for students to represent and talk about the spatial and temporal aspects of the themes. Understanding chemical phenomena at both the nanoscopic and macroscopic levels involves models that explain change with respect to time, and in chemistry, these models relate observable chemical phenomena (reactivity) with the arrangements of atoms, atoms within molecules, and atoms and molecules within networks and aggregates (structure).

Going back to our "dissolving salt in water" example, we can show how some of these themes are instantiated. As the students make decisions about the construction of a water molecule, their choices in both the types of bonds and the bond angles of the water molecule have implications for how the molecule will interact with other molecules. Here they are making *geometry*-related decisions. In the case of H_2O, the molecule is "bent" rather than linear. Because of this geometry, the molecule is polar (has unequal charge distribution), which aids in the "dissolving process" when NaCl is added to it. This decision regarding the geometric aspects of the water molecule has implications for how it will interact with the NaCl, since NaCl is "bonded" in a much different weaker way.

Continuing with this example, when the students have created a set of water molecules and begin to represent the NaCl being added to the water, they now have to show what changes, if any, take place in the NaCl and water structures. The students observe from their wet lab that the salt seems to "mix into" the water—it disappears—but that there is not an accompanying change in heat as measured by a thermometer probe. They may wonder if they need to represent a physical or chemical reaction taking place.

The students know from using a conductivity probe that the water alone does not conduct electricity, but a graph of conductivity shows that as more salt is added the solution's ability to carry a current increases. They have also been told that water molecules are "polar," but for some reason do not support an electrical current independently. They may think, "What could be happening to the NaCl after it is added to the water so that it supports a current?" As the students begin to think and talk through their representation, their decisions about changes in the spatial relationship of the atoms, ions, and molecules over time all contribute to their understanding of how the changes in connection between the various components are critical attributes of chemical identity (the "connectivity" theme.)

Since NaCl is an ionic compound, opposing electrical charges hold the Na^{+} and the Cl^{-} ions together. When NaCl is added to the water, the combination of the polarity of the water molecules (due to the *geometry* of the molecule) along with the actual number of water molecules colliding with the NaCl (*concentration*) causes the NaCl to break into its separate ions. As the students create their animation of this process, they are working with several themes in the context of a wet lab, the classroom, and the *ChemSense* environment to support their representation. It is just this type of interaction that the *ChemSense* tool and curriculum units were specifically designed to support.

The *ChemSense* tools used in the context of physical phenomena and structured classroom activities were designed to promote student thinking about representations and the chemical themes. We designed *ChemSense* resources and activities to help students focus on and understand one or more of the five themes by asking them to create animations and other representations of chemical entities and processes to reflect the spatial arrangements and temporal changes between molecules and by prompting them to discuss and revise the representations they create. The *ChemSense* environment, used along with an investigative laboratory and collaborative activities, provides a unique set of tools for students to represent and discuss their chemical ideas. The purpose of our research is to examine the role that these representational resources play in supporting students' representational practices and their emerging understanding of the nanoscopic entities and processes that underlie observable chemical phenomena.

Design Hypotheses

The purpose of design experiments, generally, is to bridge theory and educational practice (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Design-Based Research Collective, 2003; Brown, 1992; Collins, Joseph, & Beilaczyc, 2004). The intent is to both test the theories embedded in a specific design and contribute to the development of sound educational practice. Such research both documents the successes and failures of a specific design as it functions in authentic educational settings and contributes to the understanding how theoretical claims about teaching and learning can be transformed into effective learning in educational settings.

The *ChemSense* software and the corollary laboratory activities constitute an implicit set of theoretically based hypotheses about how this design will support and shape students' emergent understanding of chemistry and the development of their representational skills. In this section, we make these hypotheses explicit to serve as a guide for our subsequent analysis.

1) The *ChemSense* environment provides students with a variety of symbolic resources that they can use to jointly construct representations of the observable physical phenomena they are investigating within a set of structured collaborative activities and to explain or describe these phenomena in terms of underlying chemical entities and processes. These resources afford and constrain thinking and discourse in certain ways.

    1a) The use of specific symbolic features of *ChemSense* (e.g., "balls," "sticks," etc.) to generate a representation of specific aspects of molecular-level composition and structure (e.g., number and kinds of atoms in a molecule, relative arrangement or spatial relationship among these, atom-to-atom connections) promotes students' understanding, representation, and discussion of molecular geometry (shape), connectivity, and aggregation.

    1b) The use of specific symbolic features of *ChemSense* to generate a representation of specific aspects of intermolecular phenomena (e.g., number and proportion of molecules, relative placement of molecules) promotes students' understanding, representation, and discussion of concentration and state.

    1c) The use of the animation function of the *ChemSense* environment to represent changes within and between symbolic elements and expressions that represent the dynamic nature of molecular structures and reactions (e.g., changes in connectivity, concentration, or state) promotes students' understanding, representation, and discussion of dynamic chemical processes.

2) The ability to refer indexically to various representations constructed within *ChemSense* increases spoken discourse (e.g., describing, explaining, arguing) about both the nature of the representations and the phenomena that they are meant to represent, particularly when these activities are structured into the task or encouraged or modeled by the teacher.

3) The functionalities of the *ChemSense* tool that promote student decisions about representational elements (e.g., bonds, angles, atoms) make it likely that students will understand—and therefore meaningfully use—representational elements from other sources (including teachers and textbooks) in their class environment and integrate them into the representation they are constructing.

4) Over time and with regular use of *ChemSense* tools in the context of structured laboratory activities, students become progressively attuned to these resources and their representations become increasingly complex, infused with scientific meaning, integrated in social practice, and central to teacher-student and student-student interactions, thus promoting both chemical understanding and representational competence.

STUDY DESIGN

The design-based research described in this paper is focused on the use of *ChemSense* in the context of an authentic chemistry laboratory experience and on exploring the underlying mechanisms by which representations influence understanding in science classrooms. We pose two sorts of questions appropriate to the early stages of design research (Shavelson, Phillips, Towne, & Feuer, 2003): (1) to describe what happened and (2) to explain how it happened. First, we wanted to examine the extent to which students' chemical understanding and representational skill increased while using *ChemSense*. Second, in analyzing students' use of various features and functionality of *ChemSense*, we wanted to examine the extent to which the theory-based hypotheses built into the design of *ChemSense* might serve as tentative causal mechanisms that account for students' emerging chemical understanding and representational skill. To these ends, we used a combination of quantitative and qualitative methods. Our quantitative analyses of pretests, posttests, and student-created *ChemSense* presentations focused on students' chemical understanding and representational competence. In this regard, we document and analyze student understanding and use this analysis to identify segments of the videotaped class sessions that might shed light on the mechanisms that influenced students' conceptual and representational development, particularly in relation to the affordances the tools provided for learning. In keeping with the purposes of design research (Cobb et al., 2003), our ultimate interests are to refine the design of *ChemSense* and contribute to a theoretical base for informed educational practice.

Students, Tasks, and Contexts

The study was conducted with junior-level (grade 11) chemistry students at a San Francisco Bay Area high school serving an ethnically diverse, moderate-income community.[3] These students met for one-and-a-half hours each day, five days a week, for one semester and

[3] The largest student ethnic groups at the school include Hispanic (28%), Caucasian (26%), African-American (18%), Asian (16%), and Filipino (9%). Thirty-seven percent of students' parents hold a college degree, a figure close to the California state average. The school's Academic Performance Index in 2001 was 5 out of a possible 10 when compared with all California schools, and 8 out of 10 when compared with schools with similar demographic and achievement profiles. Only 14% of its students enroll in chemistry or physics courses, compared with an average of 36% statewide.

engaged in a variety of activities—lecture, group work, and laboratory investigations. According to their teacher, the students engaged in critical thinking and frequently used representations, creating two- and three-dimensional models of molecules as part of their curriculum.

For the study, we worked with students in two class periods (N = 24, N = 19). Within each class period, students were assigned by their teacher to lab groups of two or three students, based on student compatibility. Each group studied a 2-week-long unit on solubility (the "Solubility Module") using the *ChemSense* environment. Over the 2 weeks, students spent approximately 15 hours using *ChemSense* in conjunction with wet-lab setups and PASCO data collection tools.

The Solubility Module builds on the National Science Education Standards (National Research Council, 1996) to develop skills in inquiry, scientific discourse and explanation, and content knowledge related to structure and properties of matter and chemical reactions. The Solubility Module was designed by the *ChemSense* team (including the regular classroom teacher of the students in this study) to help students connect macroscopic observations of phenomena with nanoscopic representations and carefully examine this connection to explain observable phenomena in terms of the underlying mechanisms. This module covered a wide range of concepts related to the solubility of solids, liquids, and gases: vapor pressure and solution equilibrium, molecular solvation, miscibility, dispersion, colligative properties of solutions, and factors affecting solubility. Two of the five organizing themes—connectivity and geometry—were the predominant dimensions governing the underlying mechanisms in the solubility module. The students followed an inquiry-based approach of asking questions, carrying out student-designed investigations, analyzing data, drawing conclusions, and presenting findings (Krajcik et al., 1998).

The Solubility Module included a wide range of activities, such as creating representations in *ChemSense*, collecting data using probeware during a wet-lab investigation, and creating an HTML presentation with the built-in HTML editor. The teacher introduced the module and informed students that the work they did for this unit counted for a grade. While students worked on the various solubility activities, the teacher assumed the role of observer and "commentor," walking the lab aisles perusing student work on the computer monitors and querying them on their lab setups, data collection, and representations. By design, we wanted the teacher to be present in the classroom and available to interact with students but only provide minimal help to them during the study.

Instruments and Scoring Rubrics

A variety of instruments were used in this study to assess chemical understanding and representational competence. For the quantitative analysis, pretests and posttests developed by the *ChemSense* team and based on solubility concepts and related representations were used. Identical pretest and posttest measures were used so we could focus on fine-grained changes in representational use and student understanding on an item-by-item basis between test occasions. Because the intervention was 2 weeks long, we were not overly concerned with memory or "advanced organizer" effects between test occasions.

The test consisted of eight open-ended items that focused on connectivity, geometry, and representational issues related to solubility concepts. The response format allowed students to show their chemical understanding and representational ability in various ways. For example, one question asked students to use drawings and words to show their understanding of what a saturated solution looks like at the nanoscopic level, and another question asked students to create a graph showing how the amount of a solid that is dissolvable in a liquid changes with temperature.

The tests were scored by using connectivity, geometry, and representational competence rubrics. The connectivity and geometry rubrics were applied to different test items, depending on the chemistry content of the item—some items were scored with only one rubric, while others were scored with both rubrics. Each rubric focused on specific elements and attributes of a student's response. In the case of the geometry rubric, the award of a "correct" or "incorrect" score for an item was based on specific features of a student's response. For example, on one item students received a "correct" for showing the correct "bent shape" of a water molecule in their drawing. In contrast, the connectivity rubric was based on a more holistic scoring approach. Here an item response score from zero to four was based on overall features of the whole response. We highlight a more detailed example of the scoring in the analysis section. All items were scored by two raters; rater 1's scores were used as the actual test item scores, while rater 2's scores were used to validate rater 1's scores. High correlation ($r > .80$) between raters' scores was established. The representational competence rubric was designed to identify how students generated their representations and how they expressed their understanding through these representations. Similar to the connectivity scoring rubric, the representational competence rubric was applied in a holistic manner, based on a one to four scale. Only item 6 was scored with this rubric. Again, we highlight a more detailed example of the scoring in the analysis section.

QUANTITATIVE ANALYSES AND FINDINGS

As stated above, the primary purpose of our quantitative analyses was to describe "what happened" by examining the extent to which students' chemical understanding and representational skill increased while using *ChemSense*. In this regard, we relied on the results of our assessment instruments.

Chemical Understanding

Assessments of chemical understanding focused on two themes: geometry and connectivity. Analyzing pretest and posttest scores across these measures, we found that students' chemical understanding of solubility showed a considerable gain following the *ChemSense* solubility activities.[4] Figure 3 shows pretest and posttest score comparisons across items for geometry. For all items there was a gain between test occasions.

Two items on the test were scored with the geometry rubric. These two items were broken down into four components: 6-a, 6-b, 7-a, and 7-b. Each component was scored as either "correct" or "incorrect." Student scores on these components showed a substantial change from pretest to posttest. What do these scores mean? What were students able to do at posttest that they weren't able to do at pretest?

[4] Because several students in our study were not able to complete both the pretest and the posttest, the number of students for which test data exist is slightly less than the number of students who participated in the *ChemSense* activities.

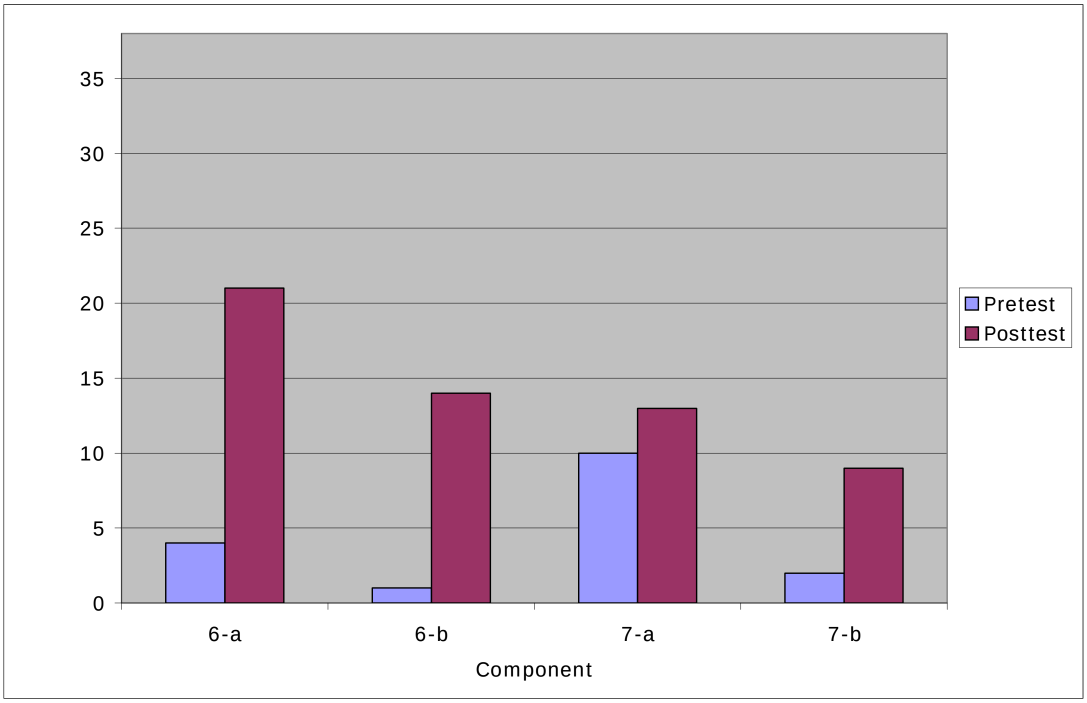


FIGURE 3. Frequency distribution of pretest and posttest score for geometry (number of students who correctly answered given item component).

Table 2 provides a description of each of the geometry components. Test item six (components 6-a, 6-b) asked students to create a four-frame storyboard showing how an ionic compound dissolves in water over time. Test item 7 (components 7-a, 7-b) asked students to describe a polar substance and explain why and how it dissolves in water.

TABLE 2

What Students Were Required to Show as Part of Their Geometry Score

Component	What Students Were Asked to Do
6-a	Show correct bent structure of water molecules
6-b	Show correct alignment of water molecules to Na^+ and Cl^- ions
7-a	Show correct polarity of water molecules

7-b	Show correct orientation of polar molecules with each other

At pretest, few students were able to represent the bent shape of a water molecule, show the charge distribution on a water molecule, show how water molecules align with each other, or correctly show the alignment of water molecules with positive and negative ions. After working through the Solubility Module, students were much more readily able to show the molecular shape and the alignment of water molecules with each other and with dissolved ions.

The connectivity rubric was applied to seven pretest/posttest items. Table 3 describes the various levels of the connectivity rubric. In general, the rubric was designed to capture student representation and discussion of changes in bonding and the related rate issues, as well as use of appropriate chemical representations and the linking of nanoscopic and macroscopic representations. By "appropriate" chemical representations, we are referring to the use of commonly accepted iconic representations to convey chemical meaning (e.g., two lines drawn between atoms to represent double bonding, electrostatic alignment between molecules to represent hydrogen bonding).

TABLE 3

General Connectivity Scoring Criteria

Level	Description
4	Accurate representation of bonding changes, relevant kinetic (rate) issues, and connection of nanoscopic and macroscopic phenomena; use of appropriate structural drawings to represent changes.
3	Partial representation of bonding changes, relevant kinetic (rate) issues, and connection of nanoscopic and macroscopic phenomena; use of appropriate structural drawings to represent changes.
2	Partial representation of bonding changes, relevant kinetic (rate) issues, and connection of nanoscopic and macroscopic phenomena;

	does not use appropriate structural drawings to represent changes.
1	Incorrect representation of bonding changes, relevant kinetic (rate) issues, and connection of nanoscopic and macroscopic phenomena; does not use appropriate structural drawings to represent changes.
0	Little or no discussion of relevant connectivity issues; does not use appropriate structural drawings to represent changes.

Figure 4 shows the distribution of students across levels at pretest and posttest. For space considerations, we present an overall connectivity level for the seven items. Here we summed the number of students at each level for each item and divided by the number of items. This effectively gave us an overall or “average” connectivity rating at pretest and posttest. In other words, Figure 4 shows the number of students who scored at each level on connectivity at the two test occasions. The comparison between the numbers of students at each level at pretest and posttest shows a positive shift in students’ understanding of connectivity-related issues. Note that this increasing trend from pretest to posttest is representative of each connectivity item score—that is, each connectivity item showed a similar positive shift from pretest to posttest. This pronounced although modest trend away from little or no discussion of connectivity issues indicates at least a partial understanding of bonding changes and rate issues.

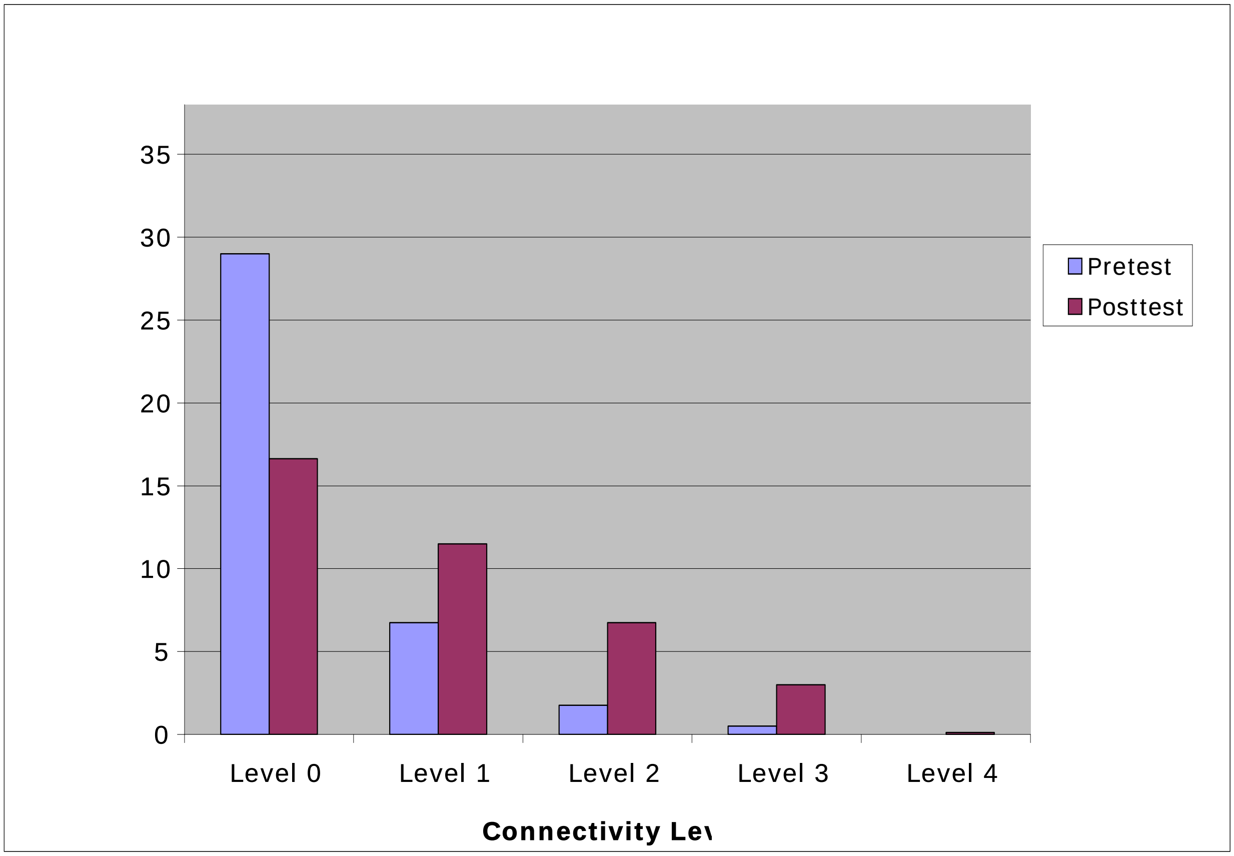


FIGURE 4. Number of students at each connectivity level at pretest and posttest, based on an average of seven items.

Representational Competence

For the representational competence rubric, we used our five-level conceptual scheme to score students on their attunement to the formal representations of chemical phenomena. As such, we rated the overall quality of a student's response rather than its "correctness." Only one item was appropriate for scoring with the representational competence rubric—the item that asked students to create a four-part storyboard showing the process of NaCl dissolving in water.

Figure 5 shows the distribution of students at each level at pretest and posttest. It is important to note that representational competence focuses on the extent to which students are attuned to the use of formal chemical representations. This differs from the "chemical accuracy" of the representations, on which students were given a chemical understanding (geometry, connectivity) score.

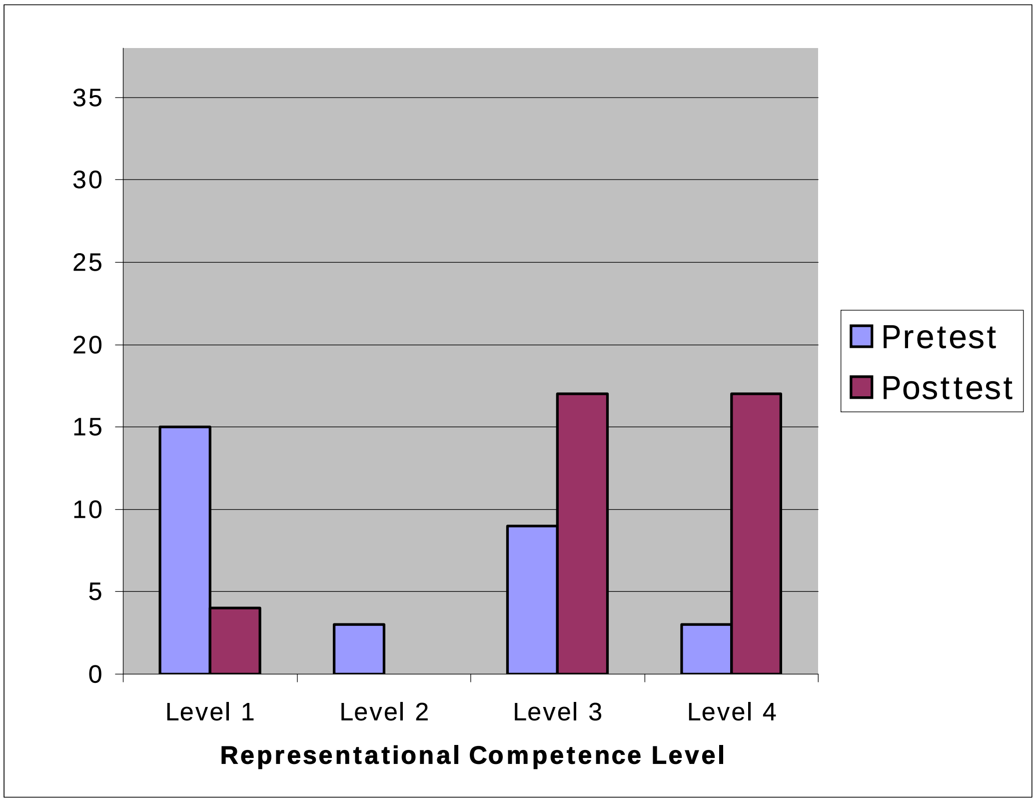


FIGURE 5. Distribution of student scores for representational competence.[5]

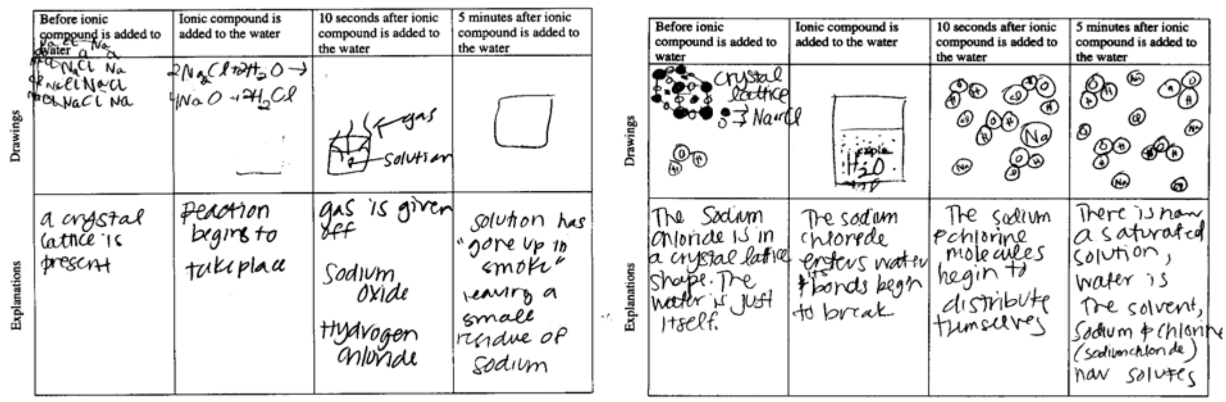
At pretest, approximately half of the students' representations were at a "representation as depiction" level (level 1). At level 1, the students were rather limited in their ability to use representations to explain physical phenomena. They tended to use representations as isomorphic, iconic depictions of a phenomenon at a point in time. A handful of students on the pretest showed "early symbolic skills" (level 2)—their representations had a mix of both surface features of the phenomenon but also used nonstandard symbolic elements to show particular

[5] At pretest, nine students left item #6 blank. At posttest only one student left this item blank.

behaviors. However, nonperceptual entities were not represented. Approximately a quarter of the students displayed “syntactic use of formal representations” (level 3)—a mix of observed physical features and unobserved, underlying entities or processes was represented. A handful of students displayed a “semantic use of formal representations” (level 4). Here students were able to correctly use formal chemical symbols to represent the underlying, nonobservable entities and processes. As expected, no students showed “reflective, rhetorical use of representations” (level 5), since the assessment was not designed to test this level of representational competence (the reason for its omission from Figure 5). At posttest, there was a distinct shift in students’ representational abilities—the vast majority of students were at representational competence levels 3 and 4. That is, students moved from a straight depiction of the physical observations at the macroscopic level to using formal representations to represent the underlying, nanoscopic-level phenomena. The fact that no students scored at level 2 at posttest brings into question the utility of this rubric. This issue will be discussed in the Discussion section at the end of the paper.

Examples of Scoring

To provide a more detailed picture of the scoring process, here we present a test item example and work though the scoring using each of the three scoring rubrics—geometry, connectivity, and representational competence. Each rubric is used as a different conceptual lens through which to examine the student’s response to this complex item. The item for this example is a four-step “storyboard” question asking students to draw and explain at the nanoscopic level how NaCl dissolves in water. This item allowed students the opportunity to show their understanding of a solubility-related *process* and represent it accordingly. We will compare pretest and posttest responses for a given student.



Pretest Posttest

FIGURE 6. Sample pretest and posttest responses.

Figure 6 shows a sample pretest response for our example test item. At pretest, the student completed all frames of the storyboard. However, instead of creating nanoscopic-level representations, the student provided a macroscopic-level drawing of the solution and a representation of the ionic lattice using the symbols "Na" and "Cl" to represent nodes in the lattice.

Using our geometry scoring rubric, this student could potentially receive points for two aspects of the response: correct polarity of the water molecules represented and correct alignment of molecules with each other. In this case, the student did not receive any "geometry" points because the response did not include a spatial representation of the H_2O molecules or the Na^+ or Cl^- ions. At posttest, it can be seen that the student accurately represented the bent shape of the water molecules, so a point was awarded. However, even though all the different entities were represented accurately—correct H_2O molecules and Na^+ and Cl^- ions—the student did not accurately represent the orientation of the water molecules relative to the ions. To receive credit for this answer, the student should have shown a convergence of multiple water molecules around a single ion and correctly shown the oxygen side of each water molecule pointed inward toward each Na^+ ion and the hydrogen side inward toward each Cl^- ion.

At pretest, the student received a level 0 score on connectivity since there were no diagrammatic or text representations of the change in the relationship between entities over time. In particular, the student did not represent the breaking up of NaCl into Na^+ and Cl^- ions or represent the connection between the macroscopic environment and the associated molecular description. At posttest, the student provided a series of representations and supportive text that showed the change in NaCl over time. Here the student showed the crystal-like lattice structure of NaCl before it was added to the water and showed the resulting dissociation of the Na and Cl once the crystal was placed in the water. However, the student did not show the dissociated Na and Cl in the water as ions—they are missing positive and negative charges. The student did provide a macroscale representation of water in a container but did not draw a connection between this and the molecular-level representations shown in the other frames. Also, the student did not represent the correct "connection" between H_2O molecules and the ions after dissociation. The student received a posttest level 3 score for providing an accurate but partially complete discussion of connectivity.

With regard to representational competence, the text descriptions and representations at pretest provide evidence that the student operated at a "surface level"—the discussion centered only on observable, macroscopic-level features. The student used representations as depictions of what might be seen at the lab bench, providing only an "isomorphic, iconic depiction of the phenomenon at a point in time." This student's response at pretest received a level 1 score. At posttest, this student demonstrated a more complex attunement to the formal representation of the underlying process. Here the student used accepted chemical symbols (space-filling molecules) to represent the underlying, nonobservable entities and processes and provided an accurate description of the dissolving process. The student showed a semantic and social use of formal representations, using these representations to explain the physical phenomena rather than simply depicting what could be seen. Note that even though this student received a very high score for this item on representational competence (level 4), the student's connectivity and geometry scores were lower because of the missing chemical information.

Our quantitative findings suggest that during the sessions in which *ChemSense* was used along with structured laboratory activities, students developed their representational competence, as well as a deeper understanding of the geometry and connectivity-related aspects of solubility. Referring again to the design research literature (Shavelson et al., 2003), our quantitative analysis helped us to understand "what happened" with respect to student learning. In light of these findings, our next step was to investigate "how this happened" by following our quantitative "leads" into the video analysis. By looking at student's representational and discursive practice as an integrated locus for learning, we attempted to gain insight into the mechanisms through which generation and use of representations iteratively lead to greater competence in using representations in developing chemistry understanding.

QUALITATIVE ANALYSIS: EPISODES FROM A *CHEMSENSE* SESSION

Having established with our quantitative analyses that some learning took place, our qualitative inquiry focused on *how* students learned by using the *ChemSense* tool. The inquiry was shaped by two interrelated considerations: the substance of what students learned and the way in which our design hypotheses might explain this learning. We used videotape to capture a detailed view of how two groups of students interacted with each other, with *ChemSense*, and with the laboratory apparatus as they worked through the Solubility Module. These data provided us with more-direct access to students' representational practices than was possible with the paper-and-pencil representational competence assessment and allowed us to understand the role that *ChemSense* played in shaping these practices and student understanding.

Consistent with a design research approach (Shavelson et al., 2003), we used our quantitative findings as an index for the specific moments in students' *ChemSense* activities that could best account for changes in student scores. Specifically, we analyzed the patterns of pre-post item responses of these two groups of students to understand "what happened" with respect to student learning. On the basis of this analysis, we were able to identify and analyze portions of the videotapes that documented the particular *ChemSense* activities in which students were most likely to have increased their chemical understanding and representational competence to better understand "why it happened." We did not intend our analysis necessarily to reveal the characteristic way in which most students in the study interacted with the tools and one another in the *ChemSense* environment. Rather, we wanted to understand important dimensions of this interaction and closely study an example of how learning *can* happen in the environment.

The two groups we taped included a total of five students: one group consisting of one boy and two girls and the second group consisting of two girls. The students came from a variety of ethnic and social backgrounds. All were juniors in high school. The two groups were chosen by the teacher on the basis of their ability to work well together and the likelihood that they would have a high level of verbal interaction. The purpose of the videotaping was to provide us with a supply of student discourse that we could use for analysis. Thus, it was imperative to have reasonably verbal and interactive students, given that we were limited to working with only two groups. We recognized that the student behaviors within these groups were not necessarily typical and therefore not generalizable. Rather, by focusing on a particular example, we hoped to illustrate how specific features of the *ChemSense* representational tools can influence student interactions and thinking, as predicted by the design hypotheses, without making claims that these specific interactions were typical of all the students in the class.

Because our qualitative analysis was intended to explain how students learned what they did, we wanted to analyze the classroom activity most closely matching the representational activity called for by the test item for which students showed the highest gain in score across the pre- and posttest measures. This item—item 6, discussed above in relation to the quantitative findings—asked students to create a four-frame storyboard of the process of NaCl dissolving in water (see Figure 6). While there were a number of classroom activities during the 2 week-long unit, the one that most closely matched the test item—and, consequently, the one to which we looked for evidence of how students came to learn the associated chemical principles—called for students to do the following:

- Using the *ChemSense* drawing tool, create a drawing that shows

  (a) Water as a liquid

  (b) Sodium chloride as a solid. Using the *ChemSense* animation tool, show what happens at a nanoscopic level when sodium chloride is added to water. Make sure you show what the solution looks like!

Except for some minor clarifications about the particulars of the assignment, the students had little guidance from the teacher or other adults in the classroom. This assignment was given on the second full day that students were using *ChemSense*. Before this assignment, students engaged in two introductory *ChemSense* activities (creating specific molecules and animating the dispersal of food coloring in water at the nanoscopic level). Although students were instructed to "show what happens at a nanoscopic level" for the target activity, their assignment in many important ways was not determined by the instructions. Students themselves needed to make practical decisions along the way: what should be shown, how it should be shown, and what their representations meant in this contextual situation.

The extended example we discuss below comes from one collaborative session that illustrates some ways in which using the *ChemSense* tool can support specific representational practices and contribute to conceptual and representational development. We purposefully chose this example because it illustrates how use of *ChemSense* might have influenced the learning process in relation to test item 6. Moreover, this extended example is long and rich enough to allow us to analyze student discourse and activity in terms of our hypotheses. The example serves as a case study of the types of ways in which *ChemSense* can support changes in students' capacity to represent their understanding through the use of tools that allow them to generate what they consider coherent representations of chemical phenomena. Most importantly, we see evidence that the *ChemSense* tools provide an additional set of symbolic resources for students to draw on as they construct their intersubjective meanings.

Episode 1

Representational Competence: Moving from Depiction of Surface Features to Deeper Symbolization of Underlying Mechanisms

In our first episode, students shift from depicting the observable features of a phenomenon to symbolizing the chemically more important nanoscopic aspects of the phenomenon. This shift occurs in two brief phases, each of which helps solidify students' orientation to a nanoscopic level of representation. In the first phase, students decide to create elaborated molecules rather than amorphous dots; in the second phase, they abandon the strategy of depicting macroscopic features of the phenomenon altogether. These changes support the hypothesis that features of the tool—specifically, those that facilitate the generation of iconic representations of atoms and molecules—shape the conceptualization of the ideas students represent by moving students away from macroscopic depictions of observable phenomena to representations of nanoscopic entities (Design Hypothesis 1a). Generally, we see in this episode an example of how the particular types of representations afforded by the tool support a particular type of discourse and a particular type of understanding.

As the episode begins, Rebecca and Kimmy face the problem of how to represent water in accord with the class assignment. They begin to draw a cup as they had done for previous assignments—what they call their "usual cup" (see Figure 7). They quickly shift from a focus on this physically observable level (blue background in rectangular container) to a deeper, chemically more interesting representation of liquid water as discrete bits of aggregated matter (beginning with iconic depictions of hydrogen molecules). After Kimmy asks Rebecca if she should show their "usual cup" with water in it, Rebecca signals the importance of the nanoscopic representation and Kimmy introduces the word "molecules" while asking Rebecca if molecules should be represented. It is important to emphasize that the students' assignment instructs them to create nanoscopic images but does not specify what a nanoscopic image is or should look like. The previous day, in order to create nanoscopic animations of food coloring dissolving, the group had used structurally amorphous dots to represent molecules of food coloring, and they did the same to represent water molecules. With this recent experience, Kimmy asks if, for this animation, they should represent the nanoscopic level using molecules or just dots. The full segment follows:

R: In the first frame—we'll make a cup.

K: Water.

R: Our usual cup.

K: Yeah. Two dimensional. Want me to do it?

R: You can do it, yeah.

K: With water in it?

R: Yup. It has to be the nano—nanoscopic water, so we have to do the, uh…

K. The molecules?

R: Yeah.

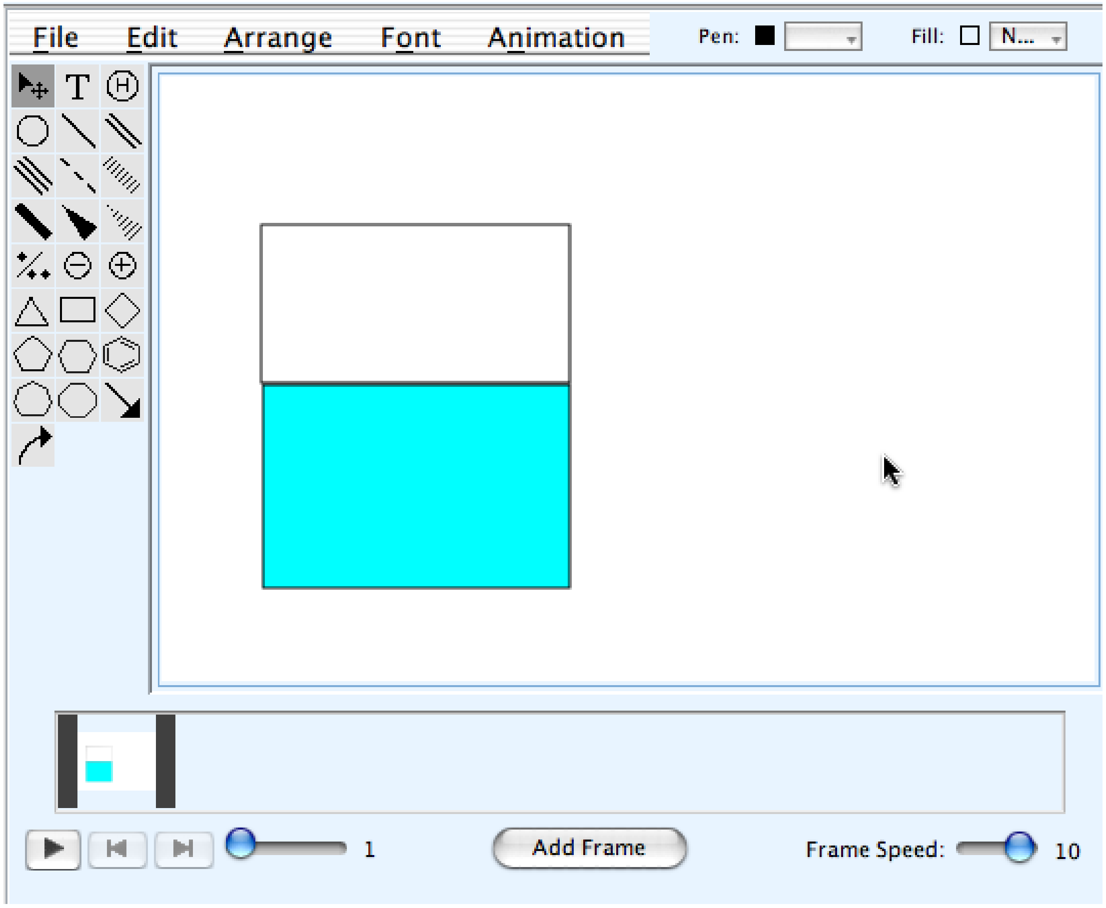


FIGURE 7. Screenshot of students' depiction of a cup.

K: The tiny ones or should they just be dots?

R: It should be small this time, really small

K: Should we make…

R: Make them, make those though…[pointing to the screen, hydrogen on the periodic table icon; see Figure 8]

K: Out of those?

R: Yeah.

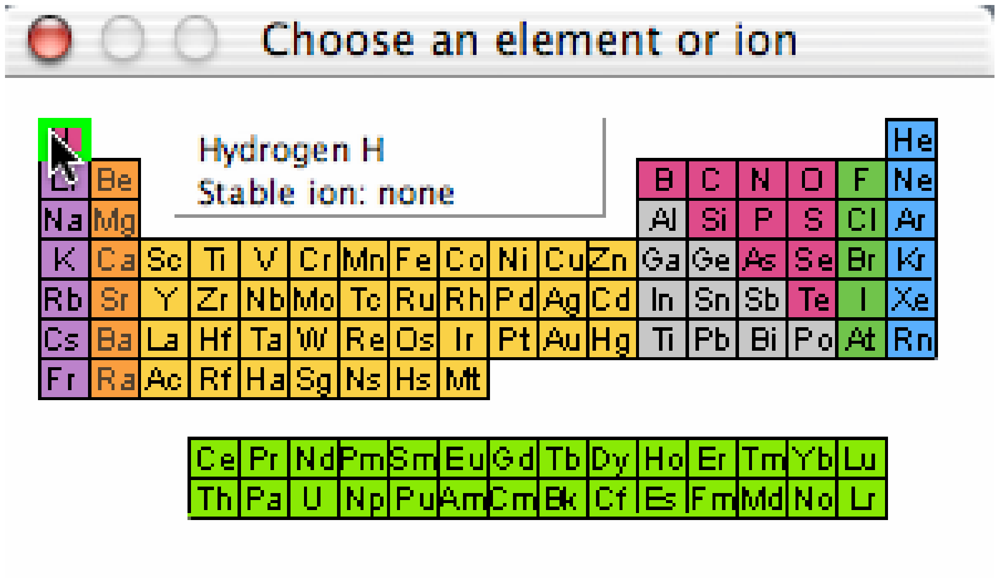


FIGURE 8. Screenshot of the atom-selection tool.

The dialogue here illustrates that certain features of the *ChemSense* tools help shape students' inclinations and choices in developing their animation. Even though the students had been drawing their "usual cup" in previous activities, they are challenged by the prospect of producing one of these cups with *ChemSense*, which does not provide a cup-drawing tool. *ChemSense* does, however, provide an atom-drawing tool that the students can use to construct molecules, which they quickly recognize is useful in their situation. The atom-selection tool before them on the screen is a shared representational resource, and as they look at it together, one of the students points to it—specifically, to the place on the periodic table representing hydrogen—and tells her partner to "make those," both students having experienced that the tool will generate individual atoms of hydrogen if they click on the "H."

Representationally, students are confronted with the basic problem of transposing their common-sense depiction of observable phenomena (depiction at level 1 or 2 in terms of our representational competence rubric) into a representation of the same phenomena at the nanoscopic level (a level 3 portrayal of unobserved causal entities and processes). This problem prompts students to use (and subsequently develop) their understanding of the aggregate, particulate nature of matter to transform their representation from a straightforward depiction of a container of water to a molecular depiction of H_2O. Ultimately, Rebecca says that depicting the cup is unnecessary and that they should show just water and sodium chloride.

The students' decision to depict molecules without a container is expressly linked to their shared experience of having previously used the *ChemSense* knowledge-sharing capacity to view an animation made by another group, which they were instructed to comment on at the end of the assignment they had just completed. Unlike Kimmy, Danny, and Rebecca, students in the other group had not depicted any type of container for the particles of food coloring and water in their animation. Fifteen or so minutes later, while the students are working to construct an image of their "usual cup," Rebecca suggests that they use the other groups' representation as a model for a new approach. We see here some evidence that as students use the representational tools, they are able to relate their emerging visual representations to other visual representations in their social environment, building on one another's pictorial contributions in much the same way that interlocutors build on one another's discursive contributions (Hypothesis 3)

R: You know what we could do—we don't even need to have a cup, though. We could just have the sodium chloride, I mean the water and the sodium chloride, like you know how that other group did when we looked at [their animation]?

K: Yeah.

At this point, we see the students shift to generating representations of phenomena fully at the particulate level, with representations that detail the structure of H_2O and NaCl molecules. Their interactions suggest that they have interpreted the assignment as requiring this level of detail to adequately show the process by which NaCl dissolves in water. Their decision to show the structure of molecules also could indicate that they are anticipating the specific representational features of the ionic reaction they will animate, with NaCl bonds breaking in the dissolving process. In this way, they would be establishing conditions for exploration of the relevant geometry and connectivity issues that relate to the creation of the molecules and animation of the dissolving process. At the same time, as students work toward adding a greater level of detail to the molecular representations, they note that they "don't even need to have a cup." In this way, they explicitly *abstract away* from the irrelevant detail of their "usual cup" (Roth, 1998)—a macro-level representation unnecessary, in this situation, for representing underlying phenomena. Although it is not possible to state that students' representations would be substantially different given a different set of tool affordances, we see here evidence that the tool supports the type of attunement the students undergo toward a more sophisticated use of formal representations.

Episode 2

Chemical Understanding: The Geometric and Connective Aspects of Turning Atoms of Hydrogen to Molecules of H_2O

After Kimmy has depicted a number of hydrogen atoms, the group moves from this subtask to the main task of depicting molecules of H_2O. The students now face a new set of representational design decisions and chemical concepts, including the ratio of hydrogen to oxygen and the basic structure of a water molecule. As Kimmy is moving the hydrogen atoms she has created apart from one another (see Figure 9), Rebecca interrupts her, saying, "Just put them all together kind of; we have to make water…" while making a small circular gesture toward the screen that probably is intended to reinforce the idea that the atoms on the screen should be closely gathered in space. As she makes her own gesture, using the cursor to circle around the hydrogen atoms, Kimmy counters that they “have to put, like, oxygen” in that space. Rebecca agrees by saying, “Oh, yeah.” At this point, the girls have used the visual plane of the computer screen to establish a shared plan for depicting water molecules as a combination of hydrogen and oxygen.

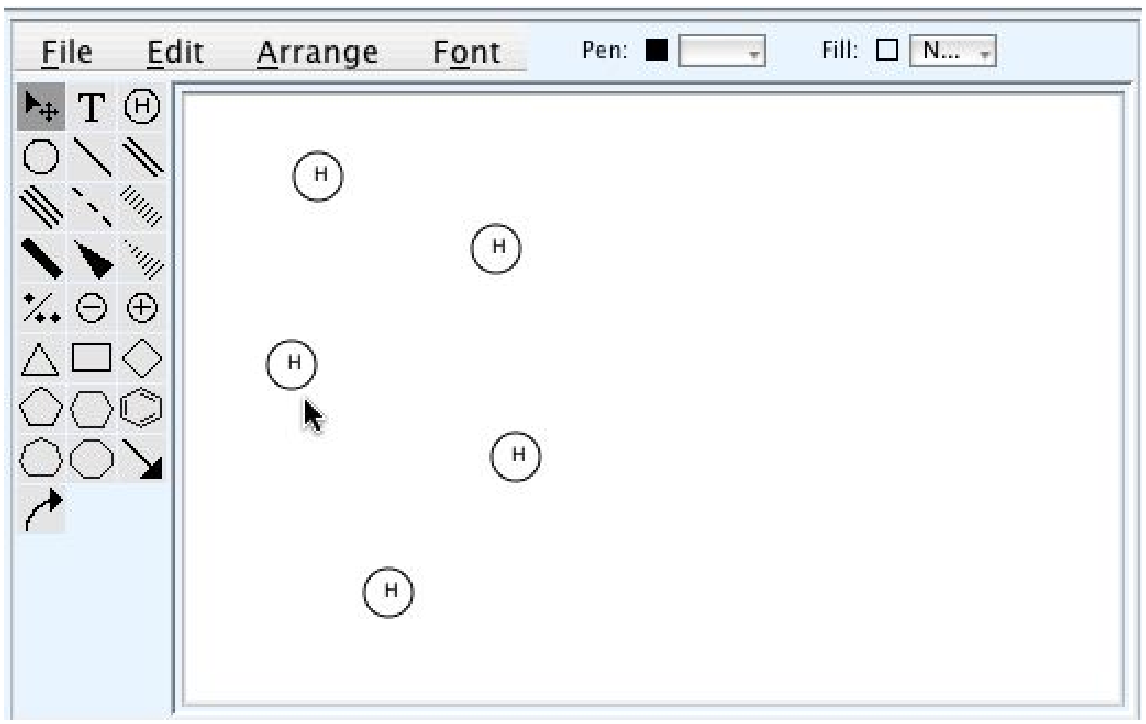


FIGURE 9. Hydrogen atoms.

But Rebecca then adds, after a 2-second pause, “One oxygen to every two hydrogen.” It seems that based on Kimmy’s gesture circling the hydrogen atoms while saying that she needs to add oxygen, Rebecca recognizes Kimmy’s misunderstanding and intention to add multiple oxygen molecules to each hydrogen. Kimmy responds, “It is, huh!” and then immediately opens the periodic table tool and begins to generate oxygen atoms. After a few seconds, Kimmy notes that she had not been thinking about the ratio of one oxygen to two hydrogen, saying, “Yeah, I forgot about that.” She makes a cluster of oxygen atoms and begins to move these atoms to form water with the hydrogen. As soon as she does so, leaving a little space between the oxygen and hydrogen, presumably to insert bonds, Rebecca offers, “Instead of just making the lines, we could just connect them and put them right next to each other so they’re bonded” (see Figure 10).

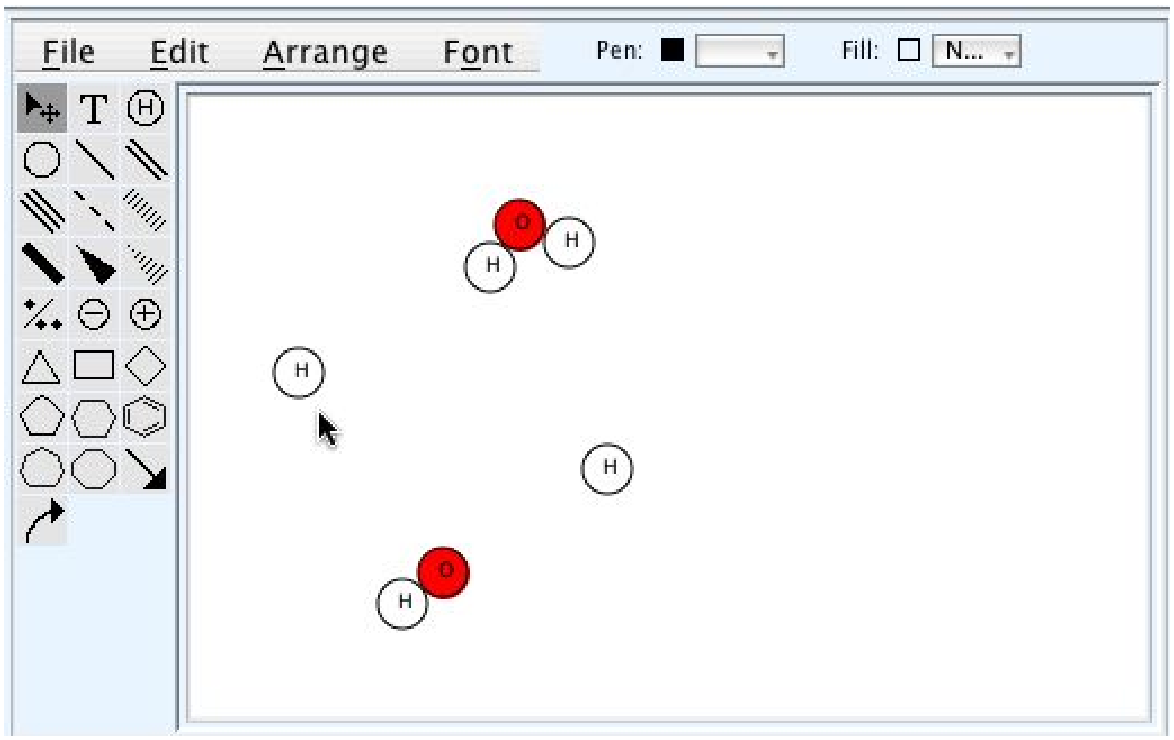


FIGURE 10. Moving hydrogen and oxygen atoms.

In the process of creating their representation, the students are explicitly and implicitly making a series of consequential decisions. First, they decide on one type of atom they need—hydrogen—selecting it from the periodic table tool *ChemSense* provides. Second, they decide that they need multiple copies of this atom, and confirm that each copy is the same size as the others, a quality of their representation that they apparently value. Third, they decide that they need additional atoms, which they also can readily generate from the tool. As the students proceed to create their representation, they face a fourth decision regarding the number of atoms in each water molecule and a fifth decision regarding the spatial arrangement of the atoms within each molecule. In what order should the molecules be aligned (H-O-H or H-H-O)? Should the molecule be linear or bent? If bent, at what angle? These issues regarding the molecule's shape, bond angles, and arrangement of atoms relate fundamentally to the geometric structure of the molecule and support conceptual development in the area of understanding molecular geometry. Finally, these students must decide how to represent the intramolecular bonds, with lines or by close proximity.

At each of these decision points, although *ChemSense* makes it easy for students to create atoms, molecules, and bonds through specialized drawing palettes, it does not provide any constraints that would steer the students away from making the "wrong" kinds or number of atoms for a water molecule, the wrong angles, or the wrong bonds. Because of what the tools afford and, importantly, how they constrain, key chemical issues, particularly the stoichiometric and geometric issues related to the nature of H_2O, come to the fore in the students' efforts. The students are no longer just showing water or generating a representation of a number of hydrogen atoms. As they work to physically construct each molecule, the tools both "remind" them of the chemistry and require them to proceed in accord with their best understanding of how water molecules are structured. They cannot avoid considering how H_2O molecules are structured because they are creating a representation of these very molecules, a process that makes them specify the key material attributes of their representations, especially those related to the stoichiometric (constituent atoms) and geometric characteristics of H_2O (Hypothesis 1a).

Episode 3

Chemical Understanding: State, Connectivity, and Geometry of H_2O

Representational Competence: Considering How to Adequately Represent Intermolecular Bonds

In this episode, Rebecca instructs Kimmy to orient the water molecules so as to imply the intermolecular hydrogen bonding that takes place between water molecules in the liquid state. Rebecca shows Kimmy how to reconfigure the molecules to orient them differently and readily move them close enough together to signify that the water in their drawing is in the liquid state (see Figure 11). Otherwise, as Rebecca notes, the molecules are "just floating all over like with gas."

R: You can make [the molecules] with a water [sic] and two hydrogens [facing] that way, so it's faced different. [pointing toward one side of the screen]

K: Make them different you want?

R: You [need to] make different shapes and different positions because you know how water is all connected sort of? Like it's not just floating all over like with gas, it's liquid water. So…you can just take …the hydrogen, you can move those around so you can make different shapes like that.

K: That'll connect to oxygens.

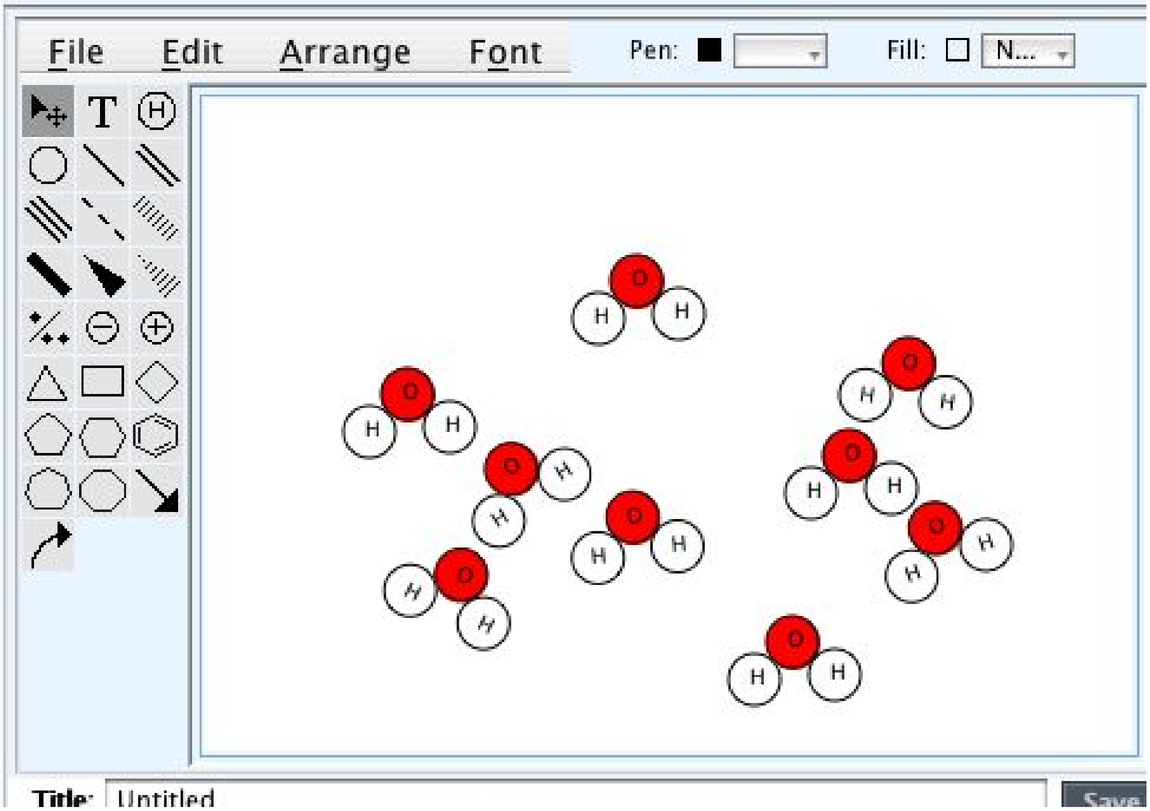


FIGURE 11. Intermolecular bonding between water molecules.

Again, we see an example in which the students apply their understanding of chemistry to the process of generating particular details of their representation. The students' chemical knowledge—related in this case to the themes of state, geometry (for liquid as opposed to solid or gaseous water), and connectivity—intertwines with their sense of what constitutes an adequate representation of hydrogen bonding (Hypotheses 1a and 1b). Just before this episode, the students agreed that proximity suffices as an adequate indication of intramolecular bonds between atoms. In this instance, the students decide that proximity *and* the orientation of molecules (oxygen of one water molecule aligned with a hydrogen of another water molecule) serve as much needed indices of intermolecular bonds—specifically, the bonds responsible for holding water in the liquid state.

The students' decision is triggered by what they have come to realize is the ambiguity of their representational meaning—does their *ChemSense* animation of H_2O look liquid or gaseous? Arranging iconic, ball-and-stick representations of water molecules in a plane, it turns out, requires students to make a design decision about the *state* of the H_2O molecules in their representation. There is an inherent meaning in the material act of placing each molecule in a particular place within the spatial plane and in a particular orientation with respect to other molecules. As students create and view their representation, they come to recognize the meaning associated with the placement and orientation of molecules. The design of *ChemSense* supports student learning of the chemical themes in two ways. On the one hand, the *ChemSense* tools force a design decision regarding the state of the molecules and an adequate representation of hydrogen bonding. On the other hand, the tools readily permit the reorientation of molecules drawn by the students, making it possible—and perhaps more likely—that students resituate molecules in their representation to express their understanding more adequately. In both these cases, tool use entails greater engagement with activity that potentially generates understanding of the connectivity and state themes (Hypotheses 1a and 1b).

Episode 4

Chemical Understanding: Attunement to Reaction Mechanisms for Changes in Connectivity

Representational Competence: Use of Expert Representations and the Leveraging of Multiple Representations

While Kimmy and Rebecca reorient the H_2O molecules on the screen to represent liquid as opposed to gaseous water, Danny begins thumbing around in his textbook—an indication that he is working to leverage and coordinate the resources available to him in the classroom—and notices a drawing of NaCl dissolving in water (see Figure 12). Although he does not specify, yet, the mechanism through which this reaction takes place, his comments show that he is using the textbook as a comparison with the students' own representation and a potential model in their efforts to show the way the water and salt molecules behave.

D: Hey, look what I found. Look, this is how it's supposed to look.

K: What?

R: That. [pointing to the picture in the book]

D: And then the water molecules each grab like…

R: Wait, where's the liquid water?

D: The liquid water's the blue stuff.

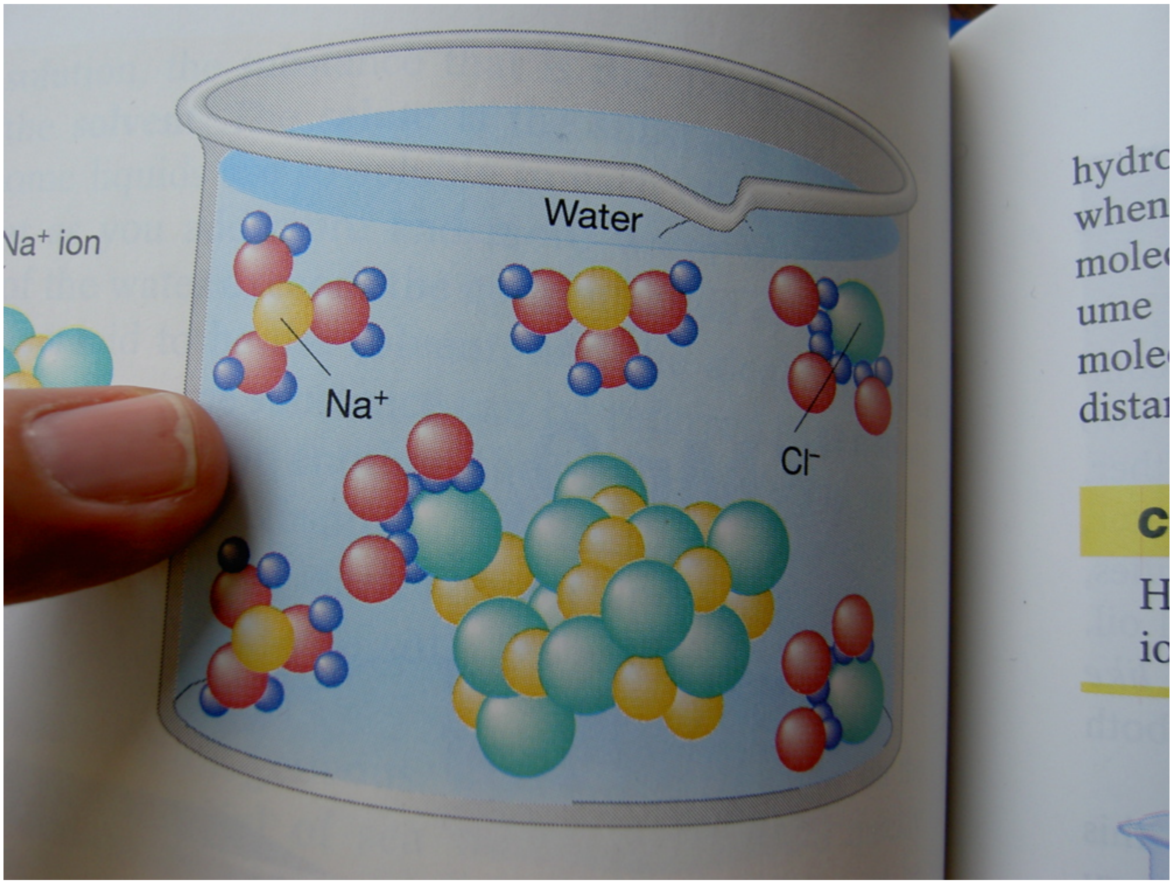


FIGURE 12. Textbook depiction of NaCl dissolving in H_2O.

R: Okay.

D: And the red and the blue thingies

R: That's the water?

D: Yeah, water molecules. And that's the salt crystal, you see how it's like the crystal? Then when it goes in, the water grabs

Danny's notion that the water "grabs" the component elements of salt is the beginning of his representational understanding of hydration and the role of polarized forces within this process, as we shall see later. Here again, we see evidence that the creation of visual representations using the *ChemSense* tools helps students create symbolic linkages to other visual representations in their social and material environment (Hypothesis 3). In this instance, the linkages are important features of a standard representation from the students' textbook. For Danny, we can argue that as he has used similar representations in *ChemSense*, these types of representations have become more salient in his perception and more meaningful to him. When he looks at his textbook, he finds representational resources that he now has a conceptual and practical framework for integrating in the representation he and his peers are creating. In this sense, he has developed what Greeno (1998) terms new attunements for seeing and meaningfully integrating representations from multiple sources into his classroom activity.

It is important to note in the students' discussion that although the textbook drawing conflates the phenomenological and nanoscopic levels in a hybrid representation, presumably for pedagogical purposes, Danny does not himself independently comment on the physical cup or the blue medium represented in the book when showing features of the molecular depiction to his partners. He seems concerned only with the nanoscopic aspects of the drawing and its relationship to the chemical phenomena the group is trying to represent. When she first sees the depiction, however, Rebecca asks, "Where's the water?" at which point Danny uses both levels of representation in his response, first indicating "the blue stuff" and adding, shortly afterwards, "And the red and the blue thingies" in reference to the molecular depiction. Rebecca asks for further clarification ("That's the water?"), which Danny provides ("Yeah, water molecules."). Although we do not know whether the hybrid feature of the textbook representation originally helped Danny orient to the nanoscopic depiction in this representation, this hybridity plays a role in Danny's explanation of the representation to his partner. Yet, despite this conversational digression, Danny brings the conversation back to his point: showing how the water "grabs" the "salt crystal." Using the textbook representation, which becomes meaningful to the students in the context of their *ChemSense* activity, the students are discursively able to specify and elaborate features of the chemical phenomenon at hand.

A short time later, while the students are animating the dissolving salt crystal, Danny does, in fact, articulate that the polarized molecules bond with one another, pointing out to the others the important features of the textbook representation (Hypothesis 2, representations as a representational resource).

D: Hey, you know what I noticed? Look.

R: What did you notice?

D: In the sodium, sodium has a positive charge, right? So [it] bonded with the oxygen, but then the chlorine bonded with the hydrogen.

R: You're so clever Danny.

D: So clever, yeah. See how the sodium bonds with the oxygen, but then the chlorine bonds with the hydrogen.

This example indicates that use of the representational tools helps students begin to leverage representations off one another as they use them in conversation—much as happened earlier when the students referenced another group's animation in deciding to dispense with their "usual cup." The students' greater capacity to relate the particular features of this textbook representation to their own representation seems to be scaffolded as they work with the tools to create similar particulars within their own representation. This "disciplinary seeing" (Stevens & Hall, 1998) comes about as students work to generate individual atoms of specific types, to bond them at certain angles, to situate them spatially, to orient them with respect to one another, and to do so as part of a larger design process aimed at representing a chemical process that occurs over a period of time. Features of this textbook representation that might have been overlooked instead become useful in students' efforts to imagine how nanoscopic phenomena actually look. In an iterative leveraging process, students' efforts to create their own representations lead to their grasp of features of an expert representation, which in turn is used to improve their own representation.

Episode 5

Bootstrapping Chemical Understanding and Representational Competence: A Chemical Solution to a Representational Problem

When students begin to animate the dissolving of the salt crystal and show the stepwise mechanism of the process, they refer to the textbook drawing again for help. As they start to create the new ionic bonds in accord with the ratio of atoms depicted in their text (see Figure 13), they notice that the numbers of H and O atoms in their own representation do not match up with the Na and Cl atoms. They discuss their mistake, saying that they should have made a smaller salt crystal or more water molecules. Finally, they resign themselves to having just a little lump of salt represented at the end of the animation—an undesired by-product of their representational process.

R: So how does it happened? Look at the book again?

D: It shows, like, a couple of water molecules bonding to one.

R: Three water molecules binding to one; maybe we should have made a smaller little crystal, huh? Maybe we should have made four in the crystal.

D: Oh, well. No, but then the crystal's still a lump right there [pointing to representation of NaCl crystal].

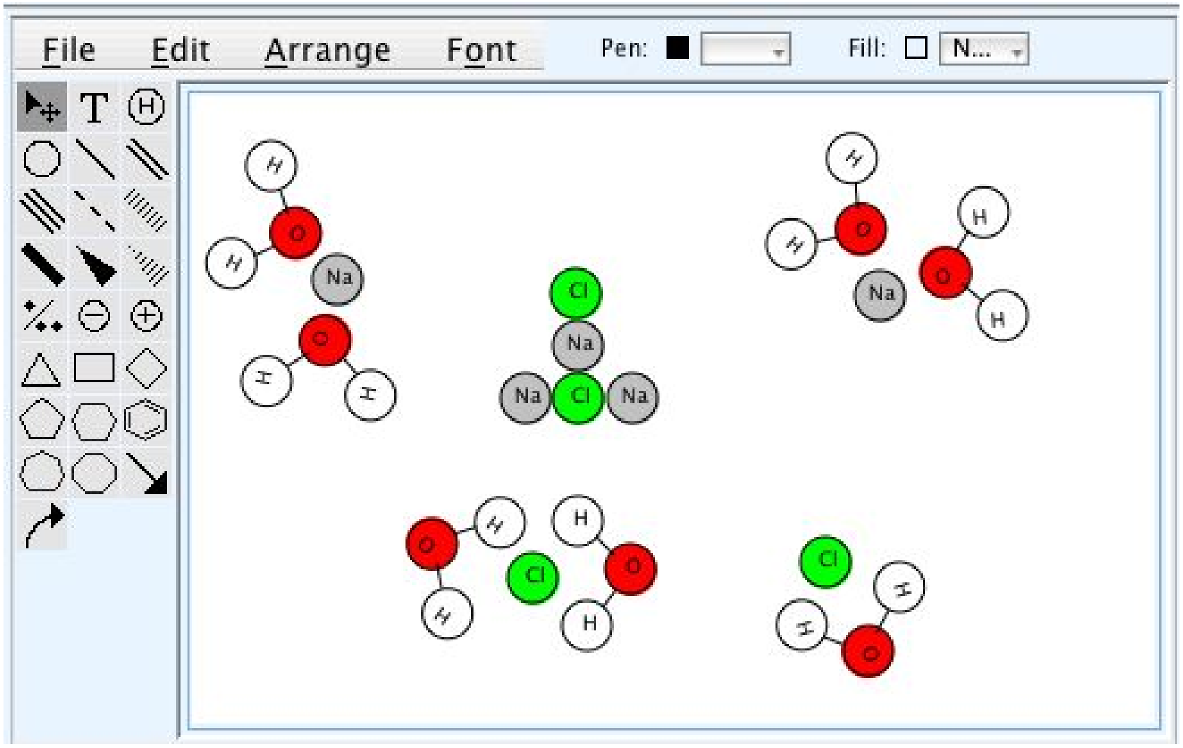


FIGURE 13. Student depiction of NaCl crystal in aqueous solution.

R: Oh, it stays lumped?

D: Yeah, it lumped.

R: But then eventually it all is done.

The undesired by-product of their representational efforts can be seen as the result of problems coordinating the spatial dimension of generating and arranging the molecules with the temporal dimension of rearranging those molecules. Over time, the molecules must be arranged differently—that is, in such manner as to represent the dissolution of NaCl and the formation of new hydrogen bonds between the water molecules and ions. The animation feature of *ChemSense* requires the stepwise reorganization of molecules within the frame and therefore is the immediate cause of the students' difficulty. However, the difficulty also promotes learning since, over time, the students map their chemical knowledge onto their representational problem and devise a chemical solution for it (Hypothesis 1c). They declare that what they have represented is a "saturated solution." The students' leftover fragments of representational material become the basis for a chemically elegant solution to their problem. This solution involves the relative proportions of the molecules being represented, which relates to the chemical theme of concentration.

D: That's the leftover, the leftover salt crystal.

R: We haven't made it completely diffuse yet then, so should we finish it? Oh, we didn't make enough hydrogen.

D: Yeah, we didn't make enough water or H_2O for that. Okay, so what do you call this?

K: That's a saturated solution.

D: Yeah, actually that's a saturated solution, so what do you title this?

This episode provides a clear example of how, first, using the tool leads the students to a representational and conceptual predicament, and, second, students use their chemistry knowledge—specifically, of saturation—to retrospectively rationalize the representation they have created. The solution works both ways: they use the chemistry to "fix" the representation, and they use the representation as a trigger to evoke and integrate a particular piece of their chemical understanding into the larger whole of their representational activity. Furthermore, we see that fixing the representation does not involve changing its actual features in any way. Instead, the students label the representation differently ("what do you call this?"), finding a chemical justification that allows them to present or position it in such way that it is responsive to both the assignment and its likely conditions of use in the classroom. In sum, we see here that a representational problem is solved by applying chemical understanding to position or situate the representation rhetorically—that is, within an anticipated context of use.

Episode 6

Representational Competence: The Social Use of Representations to Express Shared Understanding in the Classroom Setting

After a 15-minute period of struggling to write an equation for the ionic reaction (NaCl dissolving in H_2O), as specified in the *ChemSense* instructions for the day, the students ask the teacher for help. They have tried to follow the directions and finally decided on some possible equations (e.g., "H_2O +NaCl=HCL+NaO"; "H_2O +NaCl$\rightarrow$$H_2O$ Na+ H_2O Cl") to represent the phenomena they have just depicted in their animation. They want to know if they have gotten a right answer. After she examines them briefly, the teacher tells them that none of their equations are correct.

R: Let's ask Miss [Astor]. Miss Astor will you help us with something?

D: Miss Astor, we need help.

A: Yeah, what?

D: Does this [equation] look correct?

A: Oh, no.

R: Will you help us? We've been trying for a long time, and we don't understand.

D: We're trying to write this equation of adding salt water into, I mean, adding salt crystals to liquid water.

R: Are either one of these right? Which one's more right?

A: Neither.

When she prompts them to think about what happens in phenomenological terms (rather than thinking about the equation), Danny immediately points to their animation as a model of what actually happens. He also notes that the representation is "ultra-saturated," building on the students' own earlier description of their animation as "saturated."

R: Okay. So can you give us any advice on how to do it?

A: My advice is for you to think what's going to happen to sodium chloride when it goes into the water and not focus on the equation.

D: What happens? Right there. That's what happens [referring to their animation].

R: It breaks apart and binds with the oxygen.

A: Ah, that's nice. But some of it's holding together?

R: We didn't have enough water.

D: It's an ultra-saturated solution.

Although the students failed to represent the iconic reaction with an equation by failing to get a “right answer” to a standard type of chemistry question, they recognized that they had an alternative representation of the same phenomenon. In fact, Danny had earlier described their group’s animation as a “model” of what happens when salt dissolves in water. After the students’ struggles and failure in generating a correct equation in this episode, the teacher validates the visual model (“Ah, that’s nice”) as a socially meaningful embodiment of knowledge and a pedagogically relevant display of understanding, since it directly responds to her advice “to think what’s going to happen to sodium chloride when it goes into the water and not focus on the equation.” In practical terms, this interaction between teacher and student favors the iconic visual representation over the symbolic representation (i.e., the equation), indicating that the former is an important means of displaying shared knowledge in the chemistry classroom and, by extension, in the discipline. Although the students are unable to express the phenomenon at hand in the typical symbolic form ($NaCl \rightarrow [Na+]+[Cl-]$), their representation shows their understanding at the molecular level. This example also illustrates that visual representations can serve as tools for informal classroom assessment and as important “talking objects” or reference points for teacher-student and student-student interactions. Although the students had been unable to write an equation for the reaction, their animation seems to serve as a useful intermediary representation (Kozma, 2000b), pictorially embodying students’ developing understanding and probably serving as a basis for their subsequent work with the relevant formal equations.

DISCUSSION

As a design experiment, the purpose of this study was to document the learning that occurred and determine the extent to which the design theories embedded in *ChemSense* contributed to the development of students' representational competence and chemical understanding. What we learned can contribute to the development of our theoretical framework and to improvements in the design of our software environment.

Representational Competence

Our quantitative findings point to an overall increase in students' representational competence. Specifically, at pretest, students' representations tended to focus on depictions of physical observations at the macroscopic level. At posttest, students were much more able to use formal representations to stand for underlying, nanoscopic phenomena. These findings suggest that students developed their representational competence during the sessions in which *ChemSense* was used along with structured laboratory activities, a finding further supported by our analyses of students' representative practices during laboratory sessions.

From the outset, the students in the group that we closely followed began to show a progressive attunement from depicting the observable features of chemical reactions within their classroom to the use of formal representations of the underlying aspects of the phenomena they were addressing. Their incremental move away from the macroscopic container with the "dots" that they initially contemplated reflects the interrelationship between their developing understanding, the assignment they were given, and the representational resources available to them to complete the assignment—particularly those provided by *ChemSense*. Once they abandoned "their usual cup," Rebecca, Kimmy, and Danny did not revert to representing observable phenomena, and instead created discursive and visual representations that focused on the molecular level, much like the discourse of professional chemists (Kozma et al., 2000).

Although the tools presented the students with particular options—for example, from the periodic table and the symbol palette—for creating iconic representations in space and time, there was much about the ways chemical phenomena could be represented that was not constrained by the tools and was underspecified by the classroom assignment. Therefore, the students had to make a considerable number of independent decisions about the formal features of their representations that, in their estimation, adequately conveyed their understandings regarding the chemical phenomena they were investigating. For example, Rebecca and Kimmy decided against showing intramolecular bonds with lines and, instead, agreed that proximity was an adequate indicator of connectivity. We saw Danny seek out and find visual representations that could help his group develop their own representation. This is evidence that operating in the spatial domain of the *ChemSense* tool promotes consideration of and attunement to using other visual, iconic, and spatial resources that are available in the classroom environment. When the group found that they had too few hydrogen and oxygen atoms (i.e., too few water molecules) to match physically with each of the atoms in their salt crystal, they repositioned the representation in relation to the assignment they were given and vis-à-vis what the students anticipated would be the representation's conditions of use. Such an effort at positioning the representation indicates that the students recognized the differing ways a representation can function rhetorically: with a new name, a "wrong" representation can become the right product created in response to an assignment. Later, when Miss Astor provided them the option to "think what's going to happen to the sodium chloride when it goes into the water" instead of "focus[ing] on the equation," Danny presented their animation as evidence of their understanding and as the basis for the teacher's *in situ* assessment of it. For all the ways in which the *ChemSense* tool promotes thinking and decision-making about chemical concepts as they are embodied in formal features of representations, the communicative and epistemological significance of representations ultimately becomes fully realized as students use them in classroom interaction.

Both the qualitative and quantitative results support our overall contention that the use of *ChemSense* representational resources, within the social and physical contexts of collaborative laboratory investigations, can promote the development of representational competence. These findings, in turn, provide some validation for the conceptual framework and assessment approaches that we use to characterize this construct. However, there was one exception related to level 2, "Early Symbolic Skills." Although many students scored at level 1, "Representation as Depiction," and a handful of students scored at level 2 on the pretest, no students scored at level 2 on the posttest. Rather, students seemed to jump from level 1 to level 3 or 4, much as Kimmy and Rebecca did in Episode 1 when they moved from their "usual cup" to molecular representations. This finding suggests that level 2 may not be a distinct phase that students progress through on their way to higher levels of representational competence. It also suggests that additional research is needed to refine and validate our representational competence conceptual structure, assessments, and rubrics.

As with our analysis of chemical understanding, we believe that these initial findings support the speculation that extended use of *ChemSense* over a semester or a year would result in even greater gains in students' representational practices and measures of representational competence. We believe the recurring use of the *ChemSense* tool set would promote incorporation of the representations that students generate in the software environment into their regular classroom interactions and discourse.

Chemical Understanding

Our quantitative findings also indicate that, after using *ChemSense* along with structured laboratory activities for two weeks, students developed a deeper understanding of the geometry- and connectivity-related aspects of solubility. Specifically, at pretest, few students were able to correctly represent the shape or charge distribution of a water molecule, correctly show the alignment of water molecules with ions and with each other, or adequately discuss relevant connectivity issues. At posttest, students were much more able to show the shape and alignment of water molecules with each other and with dissolved ions, accurately represent correct bonding changes and connections between the macroscopic and nanoscopic levels, and use formal representations to represent the underlying, nanoscopic-level solubility phenomena.

In our qualitative analyses, we see evidence that having a representational tool, such as *ChemSense*, that readily makes iconic representations available to students helps them (1) use these representations meaningfully in their classroom practice, in ways more analogous to those of practicing chemists, and (2) conceptualize chemical phenomena in scientifically valuable ways. Examining the classroom activity of Rebecca, Danny, and Kimmy provides a window on how, by using the representational/semiotic resources provided by the *ChemSense* environment, students are able to engage in complex communication around fundamental principles of chemistry. The two-dimensional space of the computer screen, of course, is in many ways a limited representational environment, but it nonetheless channels students' activity toward constructing molecules with geometric and connective properties that are consistent with knowledge as it is represented and used within the discipline. As Rebecca and Kimmy discuss the number of atoms they need to generate representations of water molecules in Episode 2 or as they discuss the alignment of atoms within the molecule, they are necessarily engaged in consideration of core chemistry concepts regarding the structure and bonds of water molecules. As the students work to orient the molecules appropriately in relation to one another to show liquid water in Episode 3, they are confronted with representational choices that implicate their understanding of the geometric and connective aspects of phases of matter. Participating in making these choices apparent leads Danny in Episode 4 to consider the next step: how should the NaCl crystals and ions be oriented in relation to the H_2O molecules? At this point, Danny proceeds to investigate and coordinate other representational resources in his environment to answer this question, eventually calling the attention of his group members to the way that water molecules "grab" the component elements of salt. Overall, when the three students work to show underlying phenomena in terms of the specific atoms, molecules, and interactions that constitute these phenomena, they are confronted with representational choices that motivate the students to juxtapose, reorganize, and represent the verbal, iconic, and other symbolic elements available as resources in their environment. These joint findings of representational and conceptual development suggest that representational practice and understanding are mutually constitutive.

Although our quantitative results are modest, our qualitative results support the notion that extending the use of *ChemSense* across a longer stretch of students' chemistry coursework would produce even stronger positive outcomes in students' understanding. The study reported here involved the use of *ChemSense* as part of an inquiry-based activity on solution chemistry for only a relatively short time—about two weeks. But the five themes underlying chemical concepts that we develop in this article cut across all of the traditional chemistry topics—e.g., bonding, reaction rates, stoichiometry, gas laws, acid-base reactions. If these themes were developed throughout a series of *ChemSense*-based activities across a whole semester or year, we speculate that students' understanding of the chemical principles captured by these themes would increase. Recurring exploration of the themes through the use of the *ChemSense* tools could provide the basis for a deeper understanding of chemistry than students typically get from the topic-by-topic approach to the field that prevails at the high school level. The design of the *ChemSense* tools, as we have noted, reinforces the five themes by providing students an environment in which the spatial and temporal dimensions of chemical phenomena are salient. The tools put students in the position of actively constructing iconic representations of molecular phenomena in space and time, which we argue, necessarily entails, engagement with the fundamental concepts of the field.

Theoretical Contribution: Representational Constraints, Affordances, and Attunements

On the basis of our findings, we can contribute from a situative perspective to the theoretical discussion of the role of representation in understanding. The specific features of the representational resources both *constrain* and enable or *afford* the representational practices and discourse related to entities and processes that are not otherwise perceptible or available in a situation. As the students in our study become attuned to these constraints and affordances, they talk about the molecular structure of H_2O and its interaction with NaCl, as well as the physical properties of beakers, water, and salt. Consequently, the nature of the conversation becomes more "chemical," and students deepen their understanding of the molecular nature of physical phenomena that have, as a result, become chemical.

But perhaps more important, in their attunement to these representational constraints and affordances in the context of laboratory investigations and social discourse, students come to engage in representational practices that are more like those of chemists. That is, they use the affordances and constraints of the representations to pose questions, reason about answers, and warrant claims. While our observations confirm that the meaning of a specific representation emerged from the discourse around its use, rather than from the representation itself, there were features of the representations that afforded and constrained this discourse in certain ways based on the affordances and constraints that we design into *ChemSense*. For example:

- The interactions between Rebecca and Kimmy as they generated representations of water molecules and positioned them in two-dimensional space during Episodes 2 and 3 support the hypothesis (Hypothesis 1a) that the availability of tools that support the creation and positioning of “balls” of various types promotes the representation and discussion of “molecules,” their elemental composition, their structure or geometry, and their connectivity.
- The interaction between Rebecca and Kimmy in Episode 3 about the way to represent intermolecular bonds supports Hypothesis 1b, that the ability to use *ChemSense* to create numbers and proportions of different molecules and position them in certain ways supports an understanding of connectivity and aggregation.
- The use of *ChemSense* tools and other representational resources by the students to show the progression of the reaction in Episode 4 supports Hypothesis 1c, that the ability to animate the position and arrangement of these “balls” over time promotes the representation and discussion of chemical processes.
- Conversely, the lack of tools that directly represent the physical apparatus, substances, and events of the laboratory constrains the discourse and seems to reduce the discussion of such physical objects and events. The fact that Kimmy and Rebecca discontinued their use of physical depictions also seems to support Hypothesis 1, generally.
- All the episodes illustrate and support Hypothesis 2, that the ability to refer indexically to representations of chemical entities and processes that are not otherwise available in the situation increases students’ discourse about underlying chemical phenomena and how they are to be represented.

- Danny's use of textbook resources in Episode 4 and his integration of these resources into the generation of the team's representations support Hypothesis 3, that the *ChemSense* resources increase the likelihood that other representational resources will be used more meaningfully.
- Finally, the conversation between the teacher and the students in Episode 6 that resulted in Danny saying "That's what happens" as he pointed to the animation supports Hypothesis 4, that with use of *ChemSense* over time representations will become increasingly integrated into social practice and central to interactions.

Our observations show that the meaning of the students' chemical representations emerges out of their interaction with environmental features such as the *ChemSense* tools, the requirements for the assignment, the informational resources available to them, their own prior experiences, their fellow students, and their teacher. We posit that as these students engage in related wet-lab activities and representational practices in subsequent class sessions, they will be better prepared to make the laboratory phenomena become more "chemical" through the use of representations in a process through which, as Roth (in press) describes, the meaning of the symbolic representation and the physical phenomena are mutually constitutive and reify one another. Visual representations, used side by side with discursive, gestural, and other forms of meaning-making, shape and help students ground their conversation and produce shared understanding to build on one another's contributions to the interactions.

The Design of *ChemSense*

Our study was a design experiment to both test the theories embedded in our specific design and contribute to the development of sound educational practice. In light of these aims, the study reported here informed the subsequent change of several features of *ChemSense*. Although the qualitative and quantitative data we collected generally validated the design of *ChemSense*, our data also pointed us to refinements we could implement to make our tool even better. In our analysis, we found certain desirable practices that happened less often than expected or that sometimes happened despite a particular *ChemSense* design feature. Both types of occurrences provided opportunities for refinements in our design. The following is a discussion of some of the design changes that we implemented.

In part of Episode 2, Rebecca, Danny, and Kimmy used the knowledge-sharing capacity of *ChemSense* to view an animation by another group. This peer-review activity was part of their assignment and was designed to help facilitate student discourse. Even though they used this part of *ChemSense* for the purpose of peer reviewing other students' work, there was less online interaction than we originally hoped for. We noticed during our observations that there was confusion around the "build-on" metaphor that was used as part of *ChemSense* and that students had trouble understanding where new entries they created would be placed. The students were used to a more familiar "file system" metaphor, used as part of the basic file structure of most computers, rather than the more "threaded discussion" type of metaphor represented by the build-on function. Consequently, we changed the metaphor of the knowledge-sharing tool to that of a file structure to better fit students' experiences and thus make sharing within *ChemSense* as seamless as possible.

In the lab, we observed Danny, Rebecca, and Kimmy using probeware to collect data on conductivity (not reported here). They used PASCO DataStudio to monitor and record input from the sensors and the DataStudio graphing tool to generate graphs of the data. They then exported these graphs as images to be read into *ChemSense*. As mentioned earlier, the use of probeware and data-generated representations is an important resource for connecting student-generated representations to laboratory phenomena. However, these students and others ran into problems when transferring graphs from DataStudio into *ChemSense*, and this difficulty seemed to inhibit the use of these resources. Once transferred, the graphs became nonnative images within *ChemSense* and could not be edited there. Following the study, we created a way for students to import DataStudio data directly into *ChemSense* and then create graphs within the *ChemSense* tool. This change allows students to have more control over the presentation of their data, and it eliminates the need for an external graphing program. This modification is designed to increase the likelihood that these representational resources will be used regularly.

We also documented at the time of the study that students did not have a simple way of creating representations of ions. In Episode 5, Rebecca and Danny worked on creating a representation of sodium chloride dissolving in water. To represent the sodium and chloride ions at the time, Rebecca and Danny had to create the individual atoms and then add "+" or "-" symbols to represent net charge. Although this was only one extra step in the representation process for this particular example, it became apparent that other common but more complex ions, such as sulfate (SO_4^{2-}) or nitrate (NO_3^-), would require multiple steps to represent. Instead of having students step through the process of creating these chemical units by hand, we decided to integrate the most common ions as part of the available periodic table tool within *ChemSense*. With this feature, students can as readily and easily represent ions as they can atoms.

Role of the Teacher

Although *ChemSense* was designed with the collaboration of the classroom teacher in this study, the study was structured to minimize the intervention of the instructor so as to provide more openness for students' constructive use of the *ChemSense* resources. Nonetheless, the teacher in this classroom, Miss Astor, served a pivotal role in legitimizing the value in the classroom of students' visual representations as an index of their conceptual. Although at first she adhered to a "right answerism" mode of addressing the students' questions about their equations, she shifted her role to become more involved in validating the new, alternative mode of representation of chemistry concepts that emerged out of the discourse. In Episode 6, Miss Astor advised students to think about what was happening at a molecular level, rather than think about the syntax of the equation. In response, both the students and the teacher moved from the equation to the animation and began talking about the chemical processes that the equation represented, and they came to a new insight about the state of the solution (i.e., it was an "ultra-saturated" solution).

In this episode, the teacher played an important role in helping students think more deeply about the meaning of the representations that they used. This role was supported by the features of the representational resources. In this regard, our observations are consistent with those reported by Kozma (2000b) in his comparative study of student interactions in the wet lab and computer lab. In that study, because few representational resources were used in the wet lab, both teacher (TA)-to-student and peer-to-peer discussion overwhelmingly focused on the physical apparatus and outcomes with little conceptual talk. However, in the computer lab, students used software that represented the molecular structure of the substance they synthesized in the wet lab. The use of these resources changed the discourse content of both students and TAs, shifting the discussion to chemical concepts such as molecular shape, hydrogen bonding, and nonpolar groups while they used molecular modeling software that included material features corresponding to these concepts. Kozma attributes differences in the amount of conceptual talk in the two settings to differences in their material and symbolic resources.

The role of the teacher is critical in the classroom ecology and can be central not only in the design of the learning activities but also in leveraging the value of the multiple representational forms available to students through strategic discussions. Our interest in the ways in which teachers integrate visualization and modeling tools in their classroom practice has served as part of the impetus for our subsequent research using *ChemSense*. We have since recognized two significant dimensions to teacher use of new tools with their students: (1) developing plans and activities that match the tools and their pedagogical affordances to the mandated curriculum in support of learning objectives, and (2) scaffolding student learning as a result of using these tools in real time through appropriate forms of discourse (questioning, prompting, drawing students' attention to key features, verbally reinforcing the visual and vice versa, etc.). In general, by using and allowing students to use visualizations systematically as core, valid ways of representing chemical phenomena, teachers can significantly augment the traditional representational apparatus of chemistry instruction to leverage understanding at the macroscopic and mathematical levels through representations of chemical phenomena at the nanoscopic level.

Research Implications

Our current research efforts build on our findings and experiences. They focus on the role of the teacher in integrating *ChemSense* into the curriculum and ongoing classroom practice, on the effects of long-term use of *ChemSense* on student learning, and on ways in which the particular features of *ChemSense* can be improved to best support student learning, at both the high school and college levels, where students are using *ChemSense* to depict complex molecules and animate multistep reactions. Our work with classroom teachers centers on helping them develop and implement standards-based curricular activities to deepen students' understanding of core concepts that can integrate easily with the teachers' existing classroom texts and approaches. Concurrently, we are examining the effects of year-long implementation of these *ChemSense* activities on student learning. Throughout these processes, we are observing both student and teacher use of the tools and are making modifications to the design based on our findings.

The outcomes of our research depend on the successful design of curricula and tools, and also on the ways in which we assess student learning. Assessments that incorporate multiple representations—text and iconic representations—in both the question and the answer, such as those represented by the conceptual test developed by the American Chemical Society (2000, 2001), seem likely to be highly sensitive to the effects of participation in *ChemSense.* Similar to our representational competence and chemical understanding rubrics, these measures rely largely on iconic representations of molecular entities and processes in querying students' understanding of both basic and complex chemical phenomena. Since one of our primary assessment concerns is the ways in which *ChemSense* activities themselves function as embedded assessments, providing in clear, digital form views of the "chemical" meanings students make as these meanings are signified through their jointly constructed representations, types of assessment tools such as the ACS conceptual exam could provide interesting ways to triangulate measures of student learning through *ChemSense*.

Finally, our design research was conducted in the context of a particular phase of the design cycle—the early, "open-ended exploration" phase (Shavelson et al., 2003). During this phase, descriptive questions related to "what is happening?" and theory-oriented questions related to "why is it happening?" are appropriate. However, other questions are appropriate for subsequent phases in which the design is refined and further integrated into classroom practice.

Within these later phases, questions relate to systematic effects or cause and effect (Shavelson et al., 2003). Small, randomized trials within a classroom might examine which of several well-formulated design alternatives lead to a desired outcome. During the scaling-up phase, the use of experimental studies combined with case studies of implementation can test the generalizability and limits of the effects of a design as it is transported to and tested in other locales. These studies of *ChemSense* are slated for the future.

In terms of instruction, research, and assessment, the potential for visualization tools to improve classroom practice on a broad scale remains largely unexplored. While focusing on the role of the teacher in shifting classroom practice can help us better understand ways in which classroom practice can change, most chemistry teachers have had little experience with visually oriented approaches, especially approaches that systematically incorporate nanoscopic phenomena into their curriculum as representational resources that provide a common ground for students' discourse and experiences. To effect this level of change, the majority of teachers will need to think in new and sophisticated ways about chemistry content: about the quality and uses of representations students encounter; the concepts being built through their assignments; the understandings—including nonscientific conceptions—embodied in student-generated representations; the ways their feedback to students regarding their representations shapes student conceptualizations; and the means of helping students relate depictions of molecular phenomena to chemical equations and lab experiences. The need for research in this area is significant. As a research community, we are still at the beginning stages of understanding in depth and detail the processes through which use of visual representations in classroom practice can contribute to student learning.

ACKNOWLEDGEMENTS

This study is based upon work supported by the National Science Foundation under Grant No. 0125726. 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. The authors would like to thank our collaborating teachers and students for making the study possible, and would like also to thank Jeremy Roschelle, Jay Lemke, Tina Stanford, and Ken Rafanan for their feedback and assistance.

REFERENCES

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

American Chemical Society. (2001). *General chemistry (conceptual) 2001*. Washington, DC: American Chemical Society.

Amman, K., & Knorr Cetina, K. (1990). The fixation of (visual) evidence. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 85-122). Cambridge, MA: MIT Press.

Barron, B. (2003). When smart groups fail. *The Journal of the Learning Sciences, 12*(3), 307-359.

Bell, P. & Linn, M. C. (2000). Scientific arguments as learning artifacts: Designing for learning. *International Journal of Science Education, 22*(8), 797-817.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences, 2*(2), 141-178.

Brown, A. L., & Campione, J. C. (1996). Guided discovery in a community of learners. In K. McGilly (Ed.), *Classroom Lessons: Integrating cognitive theory and classroom practice*. Cambridge: MIT Press/Bradford Books.

Bunce, D., & Gabel, D. (2002). Differential effects on the achievement of males and females of teaching the particulate nature of chemistry. *Journal of Research in Science Teaching, 39*(10), 911-927.

Chi, M., Feltovich, P., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121-152.

Clark, H. H. (1996). *Using language*. New York: Cambridge University Press.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in education research. *Educational Researcher*, *32*(1), 9-13.

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *The Journal of the Learning Sciences*, *13*(1), 15-42.

Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher*, *32*(1), 5-8.

diSessa, A. A., Hammer, D., Sherin, B., & Kolpakowski, T. (1991). Inventing graphing: Meta-representational expertise in children. *Journal of Mathematical Behavior, 10*, 117-160.

Dori, Y. J., Barak, M.. & Adir, N. (2003) A Web-based chemistry course as a means to foster freshmen learning. *Journal of Chemical Education, 80*(9), 1084-1092.

Dunbar, K. (1997). How scientists really reason: Scientific reasoning in real-world laboratories. In R. Sternberg & J. Davidson (Eds.), *The nature of insight* (pp. 365-396). Cambridge, MA: MIT Press.

Gabel, D. (1998). The complexity of chemistry and implications for teaching. In B. J. Fraser & K. G. Tobin (Eds.), *International handbook of science education* (pp. 233-249). Great Britain: Klewer Academic Press.

Goodwin, C. (1995). Seeing in depth. *Social Studies of Science*, *25*, 237-274.

Greeno, J. G. (1998). The situativity of knowing, learning, and research. *American Psychologist*, *53*(1), 5-26.

Greeno, J. G., & Hall, R. P. (1997). Practicing representation: Learning with and about representational forms. *Phi Delta Kappan*, *78*, 361-367.

Hanks, W. F. (1999). Intertexts: Writings on language, utterance and context. Denver: Rowman & Littlefield.

Hinton, M. E., & Nakhleh, M. B. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions. *The Chemical Educator*, *4*(5).

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

Kozma, R. (2000a). *Representation and language: The case for representational competence in the chemistry curriculum.* Paper presented at the 16th Biennial Conference on Chemical Education, Ann Arbor, MI.

Kozma, R. (2000b). Students collaborating with computer models and physical experiments. In J. Roschelle & C. Hoadley (Eds.), *Proceedings of the Conference on Computer-Supported Collaborative Learning 1999.* Mahwah, NJ: Erlbaum.

Kozma, R. (2000c). The use of multiple representations and the social construction of understanding in chemistry. In M. Jacobson & R. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 11-45). Mahwah, NJ: Erlbaum.

Kozma, R. B., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry instruction. *The Journal of the Learning Sciences*, *9*(2), 105-143.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*(9), 949-968.

Krajcik, J. S. (1991). Developing students' understandings of chemical concepts. In S. H. Glynn, R. H. Yeany, & B. K. Britton (Eds.), *The psychology of learning science*. Hillsdale, NJ: Erlbaum.

Krajcik, J., Blumenfeld, P., Marx, R., Bass, K., Fredricks, J., & Soloway, E. (1998). Inquiry in project-based classrooms: Initial attempts by middle school students. *Journal of the Learning Sciences*, *7*(3&4), 313-351.

Lemke, J. (1990). *Talking science: Language, learning, and values*. Norwood, NJ: Ablex.

Linn, M., Bell, P., & Hsi, S. (1998). Using the Internet to enhance student understanding of science: The Knowledge Integration Environment. *Interactive Learning Environments, 6*(1-2), 4-38.

Nakhleh, M. B. (2002). *Some thoughts about molecular-level representations in conceptual problem solving.* Presented at Problem Solving in Chemistry: An Online CONFCHEM Conference on Chemistry. Available at http://www.chem.vt.edu/confchem/2002/b/nakhleh.html

Nakhleh, M. B., Lowrey, K. A., & Mitchell, R. C. (1996). Narrowing the gap between concepts and algorithms in freshman chemistry. *Journal of Chemical Education*, *73*(8), 758-762.

National Research Council. (1996). *From analysis to action: Undergraduate education in science, mathematics, engineering, and technology*. Washington, DC: National Academy Press.

Pea, R. D. (1992). Augmenting the discourse of learning with computer-based learning environments. In E. de Corte, M. Linn, & L. Verschaffel (Eds.), *Computer-based learning environments and problem-solving* (NATO Series, subseries F: Computer and System Sciences) (pp. 313-343). New York: Springer-Verlag.

Pea, R. D. (1994). Seeing what we build together: Distributed multimedia learning environments for transformative communications. *The Journal of the Learning Sciences, 3*(3), 283-298.

Roth, W.-M. (in press). What is the meaning of meaning? A case study from graphing. *Journal of Mathematical Behavior.*

Roth, W.-M. (2001). Situating cognition. *The Journal of the Learning Sciences, 10* (1&2), 27-61.

Roth, W.-M. (1998). Teaching and learning as everyday activity. In B. Fraser & K. Tobin (Eds.), *International handbook of science education* (pp 169-181). Dordrecht: Kluwer.

Roth, W.-M. (1995). Affordances of computers in teacher-student interactions: The case of interactive physics. *Journal of Research in Science Teaching, 32*, 329-347.

Roth, W.-M., & Bowen, G. M. (1999). Of cannibals, missionaries, and converts: Graphing competencies from grade 8 to professional science inside (classrooms) and outside (field/laboratory). *Science, Technology, and Human Values, 24*(2),179-212.

Scardamalia, M., & Bereiter, C. (1994). Computer support for knowledge-building communities. *The Journal of the Learning Sciences*, *3*(3), 265-283.

Schank, P., & Kozma, R. (2002). Learning chemistry through the use of a representation-based knowledge-building environment. *Journal of Computers in Mathematics and Science Teaching, 21* (3), 253-279.

Schegloff, E. (1992). Repair after next turn: The last structurally provided defense of intersubjectivity in conversation. *American Journal of Sociology, 97*(5), 1295-1345.

Shavelson, R. J., Phillips, D. C., Towne, L., & Feuer, M. J. (2003). On the science of education design studies. *Educational Researcher*, *32*(1), 25-28.

Stevens, R., & Hall, R. (1998). Disciplined perception: Learning to see in technoscience. In M. Lampert & M. L. Blunk (Eds.), *Talking mathematics in school: Studies of teaching and learning*. New York: Cambridge University Press.

Woolgar, S. (1990). Time and documents in researcher interaction: Some ways of making out what is happening in experimental science. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 123-152). Cambridge, MA: MIT Press.