Conceptual Understanding and Representational Competence in the High School Chemistry Classroom

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ABSTRACT

The purpose of this study was to explore the effects of a computer-based learning environment on high-school students’ efforts to collaboratively represent chemistry concepts during an instructional unit on solubility. The distinctive feature of this environment, called ChemSense, is that it is primarily expressive, providing students with a set of tools for drawing and animating molecular-level phenomena. Our analyses focused on two sets of constructs: (1) students’ understanding of molecular-level phenomena in terms of five comprehensive conceptual themes, and (2) students’ level of competence in using visual representations to develop and express their understanding of chemical phenomena. Although our research focused on the role the computer-based environment plays in student activity, we used a quantitative analysis of pre- and posttest data to locate chemistry concepts for which student representations seemed to be most clearly affected by their use of representational tools within the environment. Our qualitative analysis of student discussion indicates that the ChemSense environment helps students express their developing understanding of core chemistry concepts in the form of visual representations that are readily created and shared. These representations serve as key symbolic resources in students’ collaborative efforts to generate coherent explanations of the phenomena they are investigating. Creation of a shared artifact within a collectively interpreted and shaped task environment, we posit, causes students to contextualize the particulars embodied in their representation — imparting a greater level of meaningfulness and salience to these particulars.

INTRODUCTION

Growing evidence suggests that the use of visual representations supports the development of understanding in science classrooms (Barnea & Dori, 1999; Burke, Greenbowe, & Windschitl, 1998; Roth, 1996; Roth & Bowen, 1999; Sanger & Greenbowe, 2000; Wu, Krajcik, & Soloway, 2001). The role of visual representations has been of particular import to
researchers exploring chemistry education (Beall & Prescott, 1994; Francisco, Nakhleh, Nurrenburn & Miller, 2002; Nakhleh & Mitchell, 1993; Nurrenburn & Pickering, 1987; Pickering, 1990; Sawrey, 1990), a key reason being that the primary phenomena investigated in the discipline—molecules and their interactions—are for all practical purposes unobservable (Ben-Zvi, Eylon, & Silberstein, 1988; Gabel, 1998; Keig & Rubba, 1993; Kozma, 2000; Kozma, Chin, Russell, & Marx, 2000). Chemists and chemistry students are forced to understand molecular-level phenomena as they are mediated through a variety of representational forms. These forms include nonlinguistic or visual forms—such as molecular structural drawings and graphs—in addition to verbal descriptions, notational symbols, and the like.

Although several studies have shown positive correlations between student use of different types of visualization tools and measures of conceptual learning in chemistry classrooms (Barnea & Dori, 1999; Burke, Greenbowe, & Windschitl, 1998; Copolo & Hounshell, 1995; Sanger & Greenbowe, 2000; Wu, Krajcik, & Soloway, 2001), the mechanisms by which visual representations influence this development are not clear yet. In this study we investigate effects on student learning of a computer-based, representational environment called the ChemSense Knowledge Building Environment (KBE). Our findings indicate that the ChemSense environment helps students express their developing understanding of core chemistry concepts in the form of visual representations that are easy to create and to share with others. These representations serve as key symbolic resources in students’ collaborative efforts to generate coherent explanations of the phenomena they are investigating.

Although our analysis focuses on the role of the ChemSense tools, we presume that the process of generating chemistry representations using ChemSense takes place within four sets of broad, interrelated affordances and constraints (Greeno, 1998): those imposed on student activity by the ChemSense tools and interface, those entailed by the classroom assignment itself, those deriving from the discipline of chemistry, and those embedded in the social practices of the classroom and the institutional culture of the school. Yet, by maintaining our focus on the tools, we are able to show that within an appropriately organized learning environment the use of expressive tools such as ChemSense supports student discourse, helping students develop both greater depths of chemical understanding and greater competence in using chemical representations.
REPRESENTATIONS IN CHEMISTRY

High school students studying chemistry confront a novel challenge. For most, chemistry is the first subject area in which they try to systematically understand natural phenomena they cannot directly observe. Although the material tools of chemistry investigation—e.g., various solids and liquid reagents, assortments of test tubes and glassware—populate students’ laboratory experiences in chemistry class, the goal of chemistry education centers on the molecular phenomena underlying the manifest phenomena students encounter. Students must talk, read, write, and think about entities and processes taking place at a submicroscopic—or nanoscopic\(^1\)—level. To do so, like their professional counterparts in the discipline, students must rely on the use of symbolic and visual representations (Kozma, 2000). These symbolic and visual representations are, at once, both the means to their understanding of chemistry and the object of it; to learn chemistry, students must learn its representational systems. Without the possibility of being able to observe molecules or individual molecular behavior, students’ understanding of chemistry concepts depends almost entirely on their learning to operate within chemistry’s particular representational space. Operating within this space entails aligning representations with one another and with the physical-world, aperceptual referents of these representations, which proves difficult for many high-school chemistry students (Ben-Zvi, Eylon, & Silberstein 1988; Gabel, 1998; Keig & Rubba, 1993; Kozma & Russell, 1997; Nakhleh, 1992; Wu et al., 2001). The very representations on which students must rely in order to engage with the concepts of the discipline prove to be difficult for students to use and understand. Chemical representations, therefore, are both an aid and an impediment to student understanding.

Although students often have difficulties in understanding and learning from visual representations (e.g., Betrancourt, Morrison, & Tversky, 2000; Morrison & Tversky, 2001; Roschelle, 1996;), mounting evidence suggests that these difficulties can be overcome with appropriate scaffolding (Barnea & Dori, 1999; Cheng, 1999; diSessa & Friedman, 1999; Roth & McGinn, 1998), particularly if students themselves generate or manipulate the representations (Gobert & Clement, 1999; diSessa, Hammer, Sherin, & Kolpakowski, 1991; Kelly & Crawford,

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\(^1\) The “unobservable” level is often referred to in the literature as the “microscopic” level. However, individual atoms and molecules are not observable through ordinary microscopes and their size is on the order of \(10^{-9}\) meters or 1 nanometer.
1996; Meira, 1995). Studies of chemistry learning have produced similar findings (Bodner & Domin, 1996; Gabel, 1998; Williamson & Abraham, 1995; Wu et al., 2001).

REPRESENTATIONAL TECHNOLOGY AND CHEMSENSE KBE

In light of the possibility that appropriately scaffolded visualizations can help students overcome their difficulties in understanding chemical concepts, researchers have developed and investigated digitally based visualization environments for chemistry learning (e.g., Barnea & Dori, 1999; Garnett, Hackling & Oliver, 1997; Kozma, 2000; Wu et al., 2001). The shared premise underlying these efforts—which include tools such as 4M-Chem, eChem, and ChemistryExplorer—is that these representational environments provide students access to a rich visual imagery that can fill a gap in their ability to experience or imagine the world of molecular entities and reactions. Although some positive learning outcomes have been demonstrated for these visualization environments (e.g., Barnea & Dori, 1999; Burke et al., 1998; Kozma & Russell, 1997; Sanger & Greenbowe, 2000; Williamson & Abraham, 1995; Wu et al., 2001), their functionality is limited largely to viewing premade graphics (e.g., 4Mchem; Kozma & Russell, 1997) or to constructing visual representations of single molecules (e.g., eChem; Wu et al., 2001). These types of experiences reflect only limited aspects of the practices used by chemists and the conceptual understanding held by chemists about underlying phenomena.

The ChemSense KBE, in comparison, offers distinct functionalities that enable students to create their own representations of chemical phenomenon (Schank & Kozma, in press). The environment allows students to generate drawings, animations, text, and graphs, and to link these representations with one another. Specialized tools within the environment make it easy to create images of nanoscopic entities and processes. Students’ ability to readily generate representations at the nanoscopic level helps them to move from simply depicting surface features of chemical phenomena to representing underlying phenomena that align with surface features. The environment also gives students the means to coordinate nanoscopic representations with observable phenomena using probeware\(^2\) that allows students to directly import graphical or

\(^2\) 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 is collected directly into the computer, at which point it can be represented, analyzed, and imported into ChemSense.
tabular data into their representations from benchtop investigations and other inquiry-based activities (Krajcik et al., 1998; Roth & Bowen, 1999). Specially designed curriculum units scaffold student use of interconnected forms of visual and discursive representations to enable students to describe, explain, and argue about the chemical experiments they are conducting on the lab bench. The knowledge-building function of ChemSense allows students to add textual annotations to visual representations and provides a ready means for threaded discussions and commentary by students on one another’s work, thereby further supporting the possibility for students to collectively arrive at new understandings of scientific concepts (compare to Bell & Linn, 2000; Brown & Campione, 1996; Greeno, 1998; Kozma, 2000; Linn, Bell, & Hsi, 1998; Pea, 1992, 1994; Scardamalia & Bereiter, 1994).

Figure 1. The ChemSense Knowledge Building Environment (KBE) with item browsing area (upper left), preview pane (lower left), and workspace. (This workspace shows real products created by students at a San Francisco Bay Area high school in December 2000.)
In sum, ChemSense tools and pedagogical approaches are intended to help students traverse the bridge between what they can see and the unseen, underlying processes that drive chemical reactions. Our analysis of this learning process focuses on the role of ChemSense in enabling two important and interrelated lines of development: chemical understanding and representational competence.

CHEMICAL UNDERSTANDING

The underlying, fundamental chemical concepts referred to in our analysis can be systematically organized to provide a comprehensive, nanoscopic-level framework. To this end, we have developed five fundamental chemical dimensions or “themes”: connectivity, aggregation, geometry, concentration, and state. Taken together, these themes fully portray the molecular world imagined by chemists to account for observable phenomena. Each theme involves changes in molecular and supramolecular structure that correspond to critical aspects of explaining chemical reactivity. These spatially and temporally dependent themes cut across all traditional introductory chemical topics, such as acid-base reactivity, electrochemistry, solubility, kinetics, and thermodynamics. Each theme is discussed below.

The first three themes are the attributes of chemical identity. Chemical identity consists of two interrelated factors: an observation of reactivity—any observable change in a substance when acted on by any agent—and the unique chemical structure of each substance. Observations of many thousands of simple and sophisticated chemical changes have led to the development of one of the most important advances in chemistry: the structure-reactivity relationship. Chemical reactions—that is, the transformation of one set of compounds into another—involves change over time and space at the atomic and molecular level. These are changes in chemical identity and are expressed in terms of how the atoms are joined (connectivity), what the spatial relationships are between atoms in a molecule (geometry, also called stereochemistry), and the homogeneous and heterogeneous intermolecular arrangements of molecules as they cluster together (aggregation, also called supramolecular chemistry).

**Connectivity.** Connectivity is a theme that 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,
such as color, viscosity, etc. Connectivity is the non-topological map of atoms in a molecular structure.

**Geometry.** Geometry centers on the shape-related aspects of molecules. A complete understanding of chemical reactivity involves understanding the spatial relationships between entities and how changes in these relationships represent chemical change. The geometry theme has a dual focus. Molecular geometries are used when describing the arrangement of atoms in space for both stable (ground state) and unstable (trajectory/transition state) situations that prospectively give observable differences in reactivity.

**Aggregation.** The aggregation of molecules is influenced by a variety of intermolecular interactions. Aggregation refers to the emergent properties of a substance that arise based on the spatial arrangement of individual molecules (and, in the case of single atom elements, atoms). For example, aggregation forces determine why some salts dissolve in water and others do not, and why some chemical compounds mix together while others do not. Forces of aggregation play a significant role in our attempts to explain underlying biochemical phenomenon as multiple molecular units spontaneously assemble during the catalysis of specific chemical reactions. Likewise, developments within the pharmaceutical world, including drug design and mechanism of action, rely heavily on understanding the aggregation relationships that exist in molecular clusters.

The remaining two themes cover descriptions most commonly associated with the physical chemical attributes of thermodynamics (state, which covers energetics) and kinetics (concentration, which is directly related to reaction rates).

**State.** State can be defined as the full inventory of the energy relationships that exist within a set of molecules or individual atom elements. Heat, light, and the entropy of 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 process that involves a change in state. The average energy of a collection of molecules relative to the forces of aggregation will determine the phase in which a substance exists. The electronic configuration of a set of molecular orbitals might be used to define a photo-excited state. The spontaneous mixing of two gases is described in terms of one energetic state relative to another.

**Concentration.** Measures of concentration usually express the number of molecules per unit volume, unit mass, or as a ratio measured with respect to other molecules. When materials
combine to undergo chemical reactions, changes in the relationships between molecules over
time play an important role: 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, the greater the likelihood that a productive
collision will take place and the chemical reaction will proceed to the extent that accompanying
phenomenonological changes will be observed. Thus, understanding concentration and changes
in concentration plays a key role in a students learning of chemistry.

These five chemical themes guided the design of the ChemSense tools, directed
development of the curriculum and assessments used in our work. We developed the
ChemSense tools specifically to afford opportunities for students to represent and talk about the
spatial and temporal aspects of the themes. For example, as students use the tools, their
decisions about proximity, bond representations, and changes in the spatial relationship of atoms
and molecules over time are all part of understanding the connectivity theme. Similarly, students
practice and develop their understanding of state as they make decisions about the arrangements,
bond types, and possible rearrangements of molecules as reactions proceed. The activities
developed for our studies help students focus on one or more of the five themes by asking them
to create animations of chemical processes to reflect temporal and spatial changes between
molecules and by prompting them to discuss and revise the representations they create. Taken
together, the ChemSense environment provides a unique set of tools for students to represent and
discuss their chemical ideas.

REPRESENTATIONAL COMPETENCE

“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. Based on our own
research (Kozma, Chin, Russell, & Marx, 2000; Kozma & Russell, 1997) and that of others
(Amman & Knorr Cetina, 1990; Chi, Feltovich, & Glaser, 1981; diSessa, et al., 1991; Dunbar,
1997; Glaser & Chi, 1988; Goodwin, 1995; Larkin, 1983; Larkin, McDermott, Simon, & Simon,
1980; Woolgar, 1990), we use six components to define this competence:

• Using representations to explain physical phenomena

• Interpreting or explaining the meaning of a representation
• Using representations together
• Social use of representations
• Reflective use of representations
• Epistemological position of representations

We have organized characteristic patterns of these components into five stages or levels (see Table 1). We organized these components based on the assumption that the acquisition of these skills follows a developmental trajectory. This trajectory moves from the use of surface features to define phenomena which is characteristic of novices within a domain (Chi, Feltovich, & Glaser, 1981; Glaser & Chi, 1988; Kozma & Russell, 1997; Larkin, 1983; Larkin, McDermont, Simon, & Simon, 1980) — to the rhetorical use of representations, which is characteristic of expert behavior (Amman & Knorr Cetina, 1990; Goodwin, 1995; Dunbar, 1997; Kozma et al., 2000; Woolgar, 1990).

Table 1. Summary of Representational Competence Levels

<table>
<thead>
<tr>
<th>Level 1: Representation as Depiction</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
</tr>
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<table>
<thead>
<tr>
<th>Level 2: Early Symbolic Skills</th>
</tr>
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<tbody>
<tr>
<td>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.</td>
</tr>
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<table>
<thead>
<tr>
<th>Level 3: Syntactic Use of Formal Representations</th>
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</thead>
<tbody>
<tr>
<td>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 correctly use formal representations but focuses on the syntax of use, rather than the meaning of the representation. Similarly, the person is able to correctly make connections across two different representations of the same phenomenon and explain the relationship between them, but this relationship is based only on syntactic rules or shared surface features, rather than the shared, underlying meaning of the different representations and their features.</td>
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<table>
<thead>
<tr>
<th>Level 4: Semantic, Social Use of Formal Representations</th>
</tr>
</thead>
<tbody>
<tr>
<td>When asked to represent a physical phenomenon, the person spontaneously and correctly uses a formal symbol system to represent underlying, non-observable 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 and can transform one representation to another. The person is able to explain this relationship based on the shared meaning of the different representations and their features. The person spontaneously uses representations to explain a phenomenon, support a claim, or make a prediction in a social situation. The person is able to take the epistemological position that the representation corresponds to but is distinct from the phenomenon it represents.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level 5: Reflective, Rhetorical Use of Representations</th>
</tr>
</thead>
</table>
| 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 provide a common underlying meaning for several
kinds of superficially different representations and transform any given representation into an equivalent representation in another form. 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 comment on the quality of the representation based on its syntax or its semantics, vis-à-vis the phenomenon it represents. The person makes distinctions between data-generated and person-generated representations and provides reasons for the authority of one over the other. The person is able to use a formal representation in an idiosyncratic or abbreviated way that emphasizes important elements and de-emphasizes unimportant ones, vis-à-vis both some phenomenon and an intended audience. He or she is able to use features or patterns of features of one or more representations to construct an argument about entities or processes underlying observed phenomena. The person is able to take the epistemological position that we are not able to directly experience certain phenomena and these can be understood only through their representations. Consequently, this understanding is open to interpretation. Confidence in an interpretation is increased to the extent that representations can be made to correspond to each other in important ways, particularly correspondence between data-generated and human generated representations.

However, we do not feel that this trajectory is a stage-like, Piagetian progression of personal development. Rather, we ascribe to the Vygotskian notion that development depends on the person’s developmental state as well as the physical, symbolic, and social situation of the person. Research suggests that novices progressively build an understanding of science based on their interaction with events and phenomena in the world and their efforts to construct representations of these phenomena (diSessa, 2000; diSessa, in press; diSessa et al., 1991; Smith, diSessa, & Roschelle, 1993). As expertise develops, these early experiences continue to be used as intuitive examples of formal theory.

STUDY DESIGN

The study described in this paper focused on exploring underlying mechanisms by which representations influence understanding in science classrooms. To this end, we used a combination of quantitative and qualitative methods over an extended period in actual classrooms. Our quantitative analyses of pretests, posttests, and student presentations created in ChemSense focused on student understanding of the five chemical themes and students’ representational competence. Our study design did not attempt to satisfy all of the requirements of a controlled study. Rather, we were interested in identifying “entry points” into 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.
STUDENTS, TASK, AND CONTEXT

Junior-level students in two chemistry classes (N = 43) at a San Francisco Bay Area high school serving an ethnically diverse, moderate-income community participated in the study. The students met for one-and-a-half hours each day, five days a week, for one semester and engaged in a variety of activities—lecture, group work, and laboratory investigations. According to the teacher, students engaged in critical thinking and frequently employed 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 to three students based on student compatibility. Each group studied a two-week-long unit on solubility using the ChemSense environment. Over the two weeks, students spent approximately 15 hours working in the ChemSense environment in conjunction with the PASCO data collection tools.

The curriculum unit on solubility, 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 solubility of solids, liquids, and gases: vapor pressure and solution equilibrium, molecular solvation, miscibility, dispersion, colligative properties of solutions, and factors affecting solubility. Three of the five organizing themes—connectivity, geometry, and state—were the predominant dimensions governing the underlying mechanisms in the solubility module. Student work in this module followed an

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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 to all California schools, and 8 out of 10 when compared to schools with similar demographic and achievement profiles. Only 14% of its students enroll in chemistry or physics courses as compared to an average of 36% statewide (calculated as number of 9th-12th graders enrolled as a percentage of 11th and 12th graders at the school).
inquiry-based approach of asking questions, carrying out student-designed investigations, analyzing data, drawing conclusions, and presenting findings.

INSTRUMENTS AND SCORING RUBRICS

A range of instruments was used in this study to assess chemical understanding and representational competence. For the quantitative analysis, pretests and posttests were used to collect information on student chemical content knowledge and representational competence. The pretests and posttests were identical, repeated measures based on the content of the solubility module. The tests were scored using theme-based chemical-understanding rubrics in addition to a representational-competence rubric.

The chemical-understanding rubrics were designed to focus on one of the five chemical themes discussed earlier. Due to the nature of the solubility module and the lab activities that students conducted, only the most heavily implemented themes—connectivity, geometry, and state—were scored. Similarly, the representational competence rubric identified how students generated and/or discussed scientific representations, how they interpreted representations, and how they conveyed information through these representations.

At the end of the solubility module, each lab group was asked to generate a Web-based “presentation” to provide an overview of solubility activities conducted by the students, examples of their work, and summaries of their investigations. Various aspects of the presentations were scored using the rubrics described above. For example, a set of five animations was scored using the connectivity, geometry, state, and representational-competence rubrics. After a review of the presentations revealed that the majority of the student groups included few drawings but multiple animations in their presentations, it was decided to focus solely on the animations and text used to describe the animations. The information provided in the presentations typically paralleled work conducted during the solubility module activities, and presentation scores seemed to provide potential insight into places in the students’ daily activities where chemical understanding and/or representational competence might have developed.

Throughout the study, two student groups, one from each class period, were videotaped. These two groups were chosen by the teacher based on their ability to work well together and the likelihood that they would interact enough to generate data. The goal in videotaping two groups
for every class session was to generate a more comprehensive view of how students worked through the solubility module, how they interacted with one another, and what products they generated. Using the quantitative analysis as a guide, we pinpointed the chemistry activities to identify places where students were actively developing their chemical understanding and representational competence. Our videotape analysis allowed us to dig deeper into the processes behind their emergent chemical and representational understanding.

QUANTITATIVE ANALYSIS AND FINDINGS

In general, students actively engaged in using the full range of ChemSense tools. Table 2 provides a breakdown of the different types of “nodes”—text, drawing, and animation—that were created during the study.

Table 2. Quantity and Types of Nodes Created in ChemSense

<table>
<thead>
<tr>
<th>Text Notes</th>
<th>Drawings</th>
<th>Animations</th>
<th>Total Nodes</th>
<th>Avg. # Nodes/Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>372</td>
<td>240</td>
<td>270</td>
<td>882</td>
<td>46</td>
</tr>
</tbody>
</table>

Based on pretest and posttest measures, we found that students’ chemical understanding of solubility increased during the time they were engaged in ChemSense activities (Table 3). The main chemical themes articulated by students in the pretest/posttest were connectivity and geometry. Although the pretest-posttest comparison provided an overall indication that positive learning outcomes took place, it did not specifically indicate where or how this learning occurred.

Table 3. Student Pretest and Posttest Mean Scores for Connectivity and Geometry

<table>
<thead>
<tr>
<th>Connectivity (Max score: 4)</th>
<th>Geometry (Max score: 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pretest</td>
</tr>
<tr>
<td>N</td>
<td>38</td>
</tr>
<tr>
<td>Mean Score</td>
<td>.41</td>
</tr>
<tr>
<td>S.D.</td>
<td>.31</td>
</tr>
</tbody>
</table>

A closer examination of the pretest/posttest data suggests that, on average, students performed significantly better at posttest compared to pretest ($F_{\text{conn}, 1, 37} = 88.83, p < .01; F_{\text{conn}, 1, 37} =$)

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Note: several students in our study were not able to complete both the pretest and the posttest, thus the number of students we have test data on is slightly less than the number of students who participated in the ChemSense activities.
26.41, p < .01). To illustrate this difference, Figures 2 and 3 show a student’s respective pretest and posttest responses to a test item that asked students to create a storyboard showing how sodium chloride (NaCl) dissolves in water. Students were required to generate nanoscopic level drawings and provide text description beneath each drawing.

<table>
<thead>
<tr>
<th>Drawings</th>
<th>Explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before ionic compound is added to the water</td>
<td>Ionic compound is added to the water</td>
</tr>
<tr>
<td>a crystal lattice is present</td>
<td>Reaction begins to take place</td>
</tr>
</tbody>
</table>

Figure 2. Sample Student 1 Prettest Response

At pretest, the student completed all frames of the storyboard. Instead of creating nanoscopic-level representations, however, 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. The text descriptions provide evidence of a student operating at the surface level— the discussion centers only on observable features. However, at posttest the same student demonstrated more in-depth chemical understanding, as well as a higher level of representational competence, as shown in figure 3. The student displayed an accurate understanding of the dissolving process, using appropriate nanoscopic representations and text descriptions of the unobservable, underlying chemical mechanisms.
A second student displayed even more significant changes in chemical understanding and representational competence from pretest to posttest on the same test item, as shown in Figures 4 and 5 below.

Figure 3. Sample Student 1 Posttest Response

Figure 4. Sample Student 2 Pretest Response
Based on the pretest and posttest data, it is clear that students made a considerable shift in their representational competence during the study (Table 4). At pretest the mean representational competence score was 2.00. This score corresponds to a mean representational competence level at the “early symbolic skills” stage. In other words, representations of phenomenon are based on physical features but also include 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 in a static medium). However, non-perceptual or non-observed aspects of the phenomenon (e.g., molecular entities or processes) are not represented. A significant difference in representational competence mean scores were found between pretest and posttest ($F_{1,28} = 27.40, p < .01$)

<table>
<thead>
<tr>
<th>Drawings</th>
<th>Ex. NaCl</th>
<th>Ionic compound is added to the water</th>
<th>10 seconds after ionic compound is added to the water</th>
<th>5 minutes after ionic compound is added to the water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="drawing1.png" alt="Drawing" /></td>
<td><img src="drawing2.png" alt="Drawing" /></td>
<td><img src="drawing3.png" alt="Drawing" /></td>
<td><img src="drawing4.png" alt="Drawing" /></td>
</tr>
</tbody>
</table>

**Explanations**

An ionic compound consists of a metal and nonmetal. It forms a crystal that alternates from "+" to "-" ion.

As the ionic compound is added to the water, the ions slowly begin to break and begin to bond with the polar water molecules.

More bonds are being formed as time passes.

More bonds between the ion and water are made, but if the solution becomes saturated, it will begin to settle.

Figure 5. Sample Student 2 Posttest Response

<table>
<thead>
<tr>
<th>Representational Competence (Max score: 5)</th>
<th>Pretest</th>
<th>Posttest</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Mean Score</td>
<td>2.00</td>
<td>3.16</td>
</tr>
<tr>
<td>S.D.</td>
<td>1.08</td>
<td>.97</td>
</tr>
</tbody>
</table>

Table 4. Student Pretest and Posttest Mean Scores for Representational Competence
At posttest the mean representational competence level was 3.16. This places students somewhere slightly above level 3, “syntactic use of formal representations.” At this level students are able to generate representations of phenomena based on both observed physical features as well as the unobserved, underlying entities or processes (such as an unobserved cause). The representational system may be invented and idiosyncratic, and the represented entities or processes may not be scientifically accurate. The key difference between performing at level 3 compared to level 2 is that students are able to represent underlying phenomena. Students at the end of the study were better able to create drawings and animations depicting underlying chemical processes such as the motion and interaction of individual molecules.

The findings discussed above suggest that the construction of representations in ChemSense helps students develop greater representational competence as well as a deeper understanding of the geometry and connectivity-related aspects of solubility. In light of these quantitative findings, an examination of how students used the ChemSense tools allowed us to further explore the affordances the tools provided for learning. By looking at student 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 DISCUSSION: EPISODES FROM A CHEMSENSE KBE SESSION

With support from our quantitative findings—which indicate that the creation of representations in ChemSense increases both students’ representational competence and their chemical understanding—we analyzed videotapes of students generating animations using ChemSense tools. 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.

Three of the five students participated in the pretest/posttest assessment using our chemical understanding and representational competence rubrics we found that all three showed significant improvement in their chemical understanding, specifically in their understanding of “connectivity.” One showed significant improvement in the understanding of “geometry.” Another scored the highest of all students in both classes on “connectivity” and “geometry”
scores at posttest. All three students showed significant improvement in their representational competence scores as well.

In our analysis, we chose to focus on student representational activities that most closely aligned with the type of representational activity entailed in the test item for which students showed the highest gain in score across the pre- and posttest measures. This item asked students to create a four-frame storyboard of the process of NaCl dissolving in water (see Figure 2). On the second full day of students’ work with ChemSense tools, they engaged in a representational activity similar in several respects to the test item. They were given the following brief guidelines:

- 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!

Students were told verbally by the researchers that they could incorporate step 1 into step 2, using their drawings as part of their animation. Beyond this, they had little guidance from the teacher or other adults in the classroom.

Although students were instructed to “show what happens at a nanoscopic level,” 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 mean in this contextual situation. The examples we discuss below come from one collaborative groupwork session representative of modes of tool use that support representational and conceptual development. These examples indicate that changes in students’ representational competence and chemical understanding most proximately come about as students strive to resolve tensions and generate coherent chemistry
explanations using the representational tools, assignment structure, disciplinary content, and social codes of this classroom.

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 more chemically important, nanoscopic aspects of the phenomena. 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 phenomena altogether. This change suggests that the second approach is shaped by the affordances and constraints of the ChemSense tools.

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.” They quickly shift from a focus on this physically observable level (blue background in rectangular container) to a deeper, more chemically 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 this is what 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 should look like. The previous day, in order to create nanoscopic animations of food coloring dissolving, the group used structurally amorphous dots to represent molecules of food coloring, 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 “tiny [molecules] or…just dots?” The full segment follows:

R: In the first frame…we’ll make a cup.
K: Water.
R: Our usual cup.

Figure 6: Screenshot of students’ depiction of 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.
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, periodic table icon]
K: Out of those?
R: Yea.
The dialogue here illustrates that students’ attunement to certain types of familiar depictions and certain affordances of the ChemSense tools help shape their 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 using ChemSense, which does not provide a cup-drawing tool. ChemSense does, however, provide atom-drawing tools that the students can use to construct molecules, which they quickly recognize are useful in their situation.

Representationally, students are confronted with the basic problem of transposing their common-sense depiction of observable phenomena into a representation of the same phenomena at the nanoscopic level. This problem prompts students to use their understanding of the aggregate, particulate nature of matter, to transform their representation from a straightforward depiction of containers of water to a molecular depiction of $\text{H}_2\text{O}$. Ultimately, Rebecca says that depicting the cup is unnecessary, and that they should just show water and sodium chloride. After viewing others’ animations through the knowledge-building function of ChemSense, she suggests using another group’s representation as a model for a new approach.
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 it?

K: Yeah.

At this point, the students shift to generating representations of phenomena fully at the particulate level, with representations that detail the structure of H$_2$O and NaCl molecules. Their interactions indicate 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 indicates that they are anticipating the specific representational features of the ionic reaction they will animate, with NaCl bonds breaking in the solvation process. Their decisions are scaffolded through interactions with other student groups using the ChemSense knowledge-building environment.

Episode 2
Chemical Understanding: The Geometry of Turning Atoms of Hydrogen to Molecules of H$_2$O

After Kimmy has depicted a number of hydrogen atoms, the group moves from this subtask to the main task of depicting molecules of H$_2$O. The students now face a new set of chemical concepts, including the ratio of hydrogen to oxygen and the basic structure of a water molecule. Rebecca mentions that they need to make water, to which Kimmy responds, “We have to put, like, oxygen.” Rebecca adds, “One oxygen to every two hydrogen.” They both affirm this formula, and Kimmy notes that she had not been thinking about this ratio: “Yeah, I forgot about that.”

In this moment, key chemical issues, particularly the stochiometric and geometry issues related to the nature of H$_2$O, come to the fore in their 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, they are “reminded” of the chemistry and proceed in accord with their best understanding of how water molecules are structured. They cannot avoid considering how H$_2$O molecules are structured because they are creating a representation of these very molecules, a process that requires them to specify the key material attributes of their
representations, especially those related to the stochiometric (constituent atoms) and geometric characteristics of H₂O.

Episode 3
Chemical Understanding: State, Connectivity, and Geometry of H₂O
Representational Competence: Considering the Syntactic and Semantic Adequacy in Representing Intramolecular Bonds

In this episode, Rebecca instructs Kimmy to orient the water molecules so as to imply the intramolecular 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.

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.

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. Just prior to this episode, the students agreed that proximity suffices as an adequate index of intermolecular bonds. In this instance, the students decide that proximity and the orientation of molecules (oxygen of one molecule aligned with a hydrogen of another water molecule) serve as much needed indices of intramolecular 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 it look liquid or gaseous? 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 attunes students to the meaning inherent in this particular aspect of their design. As they create and view their representation, they come to recognize the meaning associated with the placement and orientation of molecules. Because the tools readily permit the
reorientation of molecules drawn by the students, students’ readily reconsider critical aspects of their design, thus supporting their engagement with critical chemical principles that must be used to create an adequate representation of hydrogen bonding.

**Episode 4**
**Chemical Understanding: Attunement to Reaction Mechanisms for Changes in Connectivity**
**Representational Competence: Semantics of Formal Representations and the Leveraging of Multiple Representations**

While Kimmy and Rebecca reorient the H$_2$O 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. Although he does not specify, yet, the mechanism through which this reaction takes place, his comments show that he is beginning to attend to 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 8: Textbook depiction of NaCl dissolving in H$_2$O.](image)

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. His attunement to and productive use of important features of this authoritative representation from the book comes in juxtaposition to his experiences generating representations with his group.

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, again signaling to his peers his own attunements and pointing out to them the important features of the textbook representation.

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. Their greater attunement to the particular features of this textbook representation seems to be scaffolded by the attunements that develop 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 vivid icons of the way students can now imagine the nanoscopic phenomena actually look. In the iterative leveraging process, student efforts to create their own vivid, iconic representations lead to their grasp of features of an authoritative 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 step-wise mechanism of the process, they refer to the textbook drawing for help. As they start to create the new, ionic bonds in accord with the ratio of atoms depicted in their text, 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.
Figure 9: Student depiction of NaCl crystal in H₂O solution.

R: Oh, it stays lumped?
D: Yeah, it lumped.
R: But then eventually it all is done.

However, over time the students devise a chemical solution to their representational problem. They declare that what they have represented is a “saturated solution.” The students’ “left-over bits” of representational material become the basis for a chemically elegant solution to their problem, a solution that implicates the chemical dimensions of aggregation, concentration, and connectivity.

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 H₂O 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 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, mobilize, and integrate a particular piece of their chemical understanding into the larger whole of their representational activity.

Episode 6
Representational Competence: The Social Use of Representations to Express Understanding in the Classroom Setting

After a fifteen-minute period of struggling to write an equation for the ionic reaction (NaCl dissolving in H₂O), as specified in the ChemSense instructions for the day, the students
ask the teacher for help. The teacher tells them that none of their equations are correct. 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: Let’s ask Miss [Ashcroft]. Miss Ashcroft will you help us with something?
D: Miss Ashcroft we need help.
A: Yeah, what?
D: Does this 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.
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].
Figure 10: Student depiction of NaCl crystal in H₂O solution.

K: It breaks apart and binds with the oxygen.
R: We didn’t have enough water.
D: It’s an ultra saturated solution.

Danny had earlier described their group’s animation as a “model” of what happens when salt dissolves in water. The teacher, in this episode, validates this visual model as a socially meaningful embodiment of knowledge and a pedagogically relevant display of understanding. 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 knowledge in the chemistry classroom, and, by extension, in the discipline. 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, as well, student-student interactions. Although the students had been unable to write an equation for the reaction, their animation seems to serve as an icon-rich “hook” (Kozma, 2000), pictorially embodying their developing understanding and likely serving as a basis for their subsequent work with the relevant formal equations.
DISCUSSION

The episodes presented here show on a fine-scale level how creating representations drives student explanations, and how in turn these explanations tie student representations meaningfully into broader sets of classroom activities. In our analysis, we are able to locate points at which students discursively engage with the themes underlying chemical phenomena, and show that movement along the trajectory of conceptual growth is intertwined with students’ emerging representational competence. Students’ representational efforts move from depiction of observable features of solvation (cups, water) to deeper symbolization of underlying mechanisms of the process at the molecular level and to reflective, rhetorical use of their animation for reconsidering and rationalizing earlier design decisions.

Our examples also show that by generating visual representations for the purposes of explanation in the classroom, students can experience an epistemological shift both in relation to the role of representations for communicating understanding, and in relation to their own capacity to express and display chemically meaningful ideas. Visual representations in themselves can embody meaningful chemical knowledge; in the final episodes we see that with the teacher’s support Danny, and his peers point to their animation as a reasonable and sufficient account of how NaCl dissolves in H$_2$O. This example suggests that students who may not yet have appropriated the linguistic or notational capacity to express their conceptualization of phenomena in formal, symbolic terms can nonetheless express and develop their understanding through alternative means. Specifically, student learning can be enhanced through social interaction centered on iconic, intermediary forms—effectively, the “new symbolic representations” that Kozma (2000) argues are essential as a point of translation and engagement for students learning difficult scientific concepts or abstract symbolic formulations.

As we see, the “new symbolic representations” students generate using ChemSense tools take on their meanings within the particular task structures and discourse practices of classroom activity. These types of representations are often nonstandard in form, constructed in ways that help students develop their understanding and “serve immediate local purposes” (Greeno & Hall, 1997). As student creations, these representations stand apart from intermediary representations generated by teachers or other experts. These latter representations have “surface features that correspond to and behave like scientific entities” and can therefore “help students make the mental connections necessary to integrate conceptual entities, real-world situations, and symbolic
expressions used by experts” (Kozma, 2000: 19). However, these intermediary representations alone do not make it possible for students to see the correspondence between the surface features of the representations and the scientific entities that they are supposed to represent (Roschelle, 1996). Instead, interpretation of intermediary representations must be elicited through discursive social processes, examples of which we see in our analysis. Roschelle calls this type of process or interaction “mediated collaborative inquiry” (1996: 2), emphasizing the role representations play in enabling learners to construct and share meanings.

The particular value of the ChemSense tool lies in the ease with which students can move individual and collective entities relative to one another in space and in time, thereby generating animations of molecular-level phenomena. As students resolve constraints while working out the details of generating these types of representations, they engage with graphic elements that are isomorphic to the five key chemical themes we have identified and outlined in this paper: connectivity, geometry, state, aggregation, and concentration. Because it is easier for students working in the ChemSense environment to resolve constraints in certain ways over others, their representational efforts are continuously channeled towards the creation of artifacts in ways that entail engagement with the spatial and temporal dimensions underlying the five chemical themes. The artifacts generated out of this process, for their part, do not stand alone, but rather are necessarily integrated within the broader framework of meaning that students collectively create for themselves while using these representational tools. The constraints and affordances of the ChemSense tools, therefore, instantiate the key mechanism for leveraging greater chemical understanding through greater representational competence: By readily affording students the means to create molecular-level animations, ChemSense also supports them in assigning meaning to these animations in relation to the task at hand, the subject area of chemistry, and the social interactions of their classroom.

Through their participation in a complex process of giving meaning to the details of their representational activity, the students we observed showed indications of developing what we characterize as progressively greater attunement (Greeno, 1998) to disciplinary ways of seeing (and using) representations (Goodwin, 1995; Stevens & Hall, 1998;). Creation of a shared artifact within a collectively interpreted and shaped task environment, we posit, causes students to contextualize the particulars embodied in their representation— imparting a greater level of meaningfulness and salience to these particulars. In turn, students make use of this newly found
significance of particular features of their own representations by applying it to other representations—representations generated by themselves, by peers, or by experts, including teachers and textbooks. From this perspective, the development of representational competence depends on students coming to see in a disciplined way, and to use these new perceptual and interpretive tools for problem-solving in specific areas of practice.

Delving further into the functionalities of the tools, we see that although the ChemSense environment includes a wide range of affordances for students to create nanoscopic representations, these are balanced against a number of functions that the environment, by design, does not afford. Although students can select atoms and bond types to generate representations of molecules, there are no built-in constraints that prevent students from creating chemically “impossible” representations; ChemSense allows students to make mistakes. Because there are few automatic or “smart” features in the environment, students using ChemSense make multiple design decisions about what they create. For example, when a student wants to create a water molecule, the individual components of the molecule (one oxygen and two hydrogen atoms), number and type of bonds (i.e., two single bonds), and angles between the atoms (i.e., $105^\circ$) have to be determined by the student. There is no “Create H$_2$O Molecule” tool, nor is there a function that automatically snaps the atoms together at an appropriate angle or stops the student from inserting a double bond. To make their own design decisions, students need to think critically about the entities and processes they are representing.

Among its most significant functions, the ChemSense environment allows students to create externalized and visually accessible models of chemical entities and processes that in themselves become material resources and reference points for further representations, whether visual or discursive. ChemSense makes it possible for students to create—individually or collaboratively—and share—face-to-face or virtually—their images of chemical phenomena in a way that readily affords social use of these images. Used in conjunction with inquiry-oriented curriculum activities designed to take advantage of its features, ChemSense becomes a tool for creating and circulating key material resources within the social environment of the classroom; it becomes an actual knowledge-building environment. ChemSense, therefore, directly supports use of visual representations in the scientific discourse of the classroom, discourse that ideally elaborates and converges upon key concepts within the discipline. As students learn to display their developing understanding of chemical concepts and use the visual representations they
create with the tools to argue their positions, they can progress towards more advanced, inclusive levels of representational competence, in which their representations become reflectively and rhetorically incorporated into their scientific practice (Kozma et al., 2000). Similarly, representational activity within the ChemSense environment holds out the promise for enhancing learning by causing students to make and justify specific design choices that require reflection on and explanation of the conceptual underpinnings of chemistry.

CONCLUSION

Even used in a limited way in an otherwise standard chemistry classroom, the ChemSense Knowledge Building Environment offers students a promising means through which to construct and express chemical knowledge. An analysis of the process through which students generated animated representations provides evidence that students integrate representations into their classroom practice as one of many types of semiotic resources that finds meaningful articulation with the others. Also, we see that representational competence and chemical understanding improve together; that is, students’ capacity in each of these areas promotes growth in the other. As the ChemSense research program expands, greater teacher training and a more sustained, integrated approach to using ChemSense at various levels of chemistry learning should provide a clearer understanding of the role of student-student and teacher-student discourse in promoting more productive representational practice in chemistry learning. Additionally, we hypothesize that more sustained and integrated use of representational tools such as ChemSense will alter some basic teacher preconceptions about the means through which students can learn and communicate their scientific knowledge.
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