Material and Social Affordances of Multiple Representations for Science Understanding[1]

Robert Kozma
Center for Technology in Learning
SRI International

This article reviews experimental and ethnographic studies conducted by our research group to examine the role of multiple representations in understanding science. It examines the differences between expert chemists and chemistry students in their representational skills and in their use of representations in science laboratories. It describes the way scientists use the material and social affordances of multiple representations to support their shared understanding and laboratory practices and contrasts this with the way students use representations. While scientists coordinate features within and across multiple representations to negotiate shared understanding, students have difficulty moving across or connecting multiple representations, so their understanding and discourse is constrained by the features of individual representations. Implications are drawn for the design and use of technology-based systems that provide students with coordinated, multiple representations and collaborative activities that can support the development of shared understanding in science. These implications are explored in a pilot study.

There is a significant body of research that establishes the benefits of using multimedia and multiple representations in the learning of school knowledge (Schnotz & Kulhavy, 1994; van Sommeren, Reimann, Boshuizen, & de Jong, 1998). The emphasis of this research is on the impact of multimedia—specifically, coordinated visual and verbal representations—on students' cognitive structures and processes. For example, Mayer (in press) makes a compelling case that the presentation of information in both visual (pictures or animations) and verbal (text or narration) forms increases recall and problem solving transfer by helping learners encode this information in both visual and verbal forms and integrate these in long-term memory.

The research reported in this article takes a different perspective on multiple representations. It looks at the material and social affordances that multiple representations provide in support of science understanding. That is, it examines research on how scientists coordinate the features of multiple representations to construct a shared understanding of the scientific phenomena that is the focus of their laboratory work. The representational skills and practices of scientists are contrasted with those of students.

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The findings of these studies have implications for the design of instructional environments that support student understanding in science, particularly the design and use of technology-based representational environments. These implications are also explored in this article.

The theoretical perspective taken in this article draws on a situative approach to learning (Greeno, 1998; Brown, Collins, & Duguid, 1989; Resnick, 1988). The situative approach characterizes understanding in terms of people's participation in practices of inquiry and discourse that include interactions with others and with the material and technological resources of their environment. This approach emphasizes the situated processes by which people come to collaboratively construct shared meaning within a particular social, material, and symbolic context. When viewed within a social context, scientific inquiry is seen as an emergent interaction among scientists and between scientists and their materials at hand. Representations are among the material objects that support the discourse and meaning-making of a scientific community of practice. The features of various representations, singularly and together, afford certain ways of thinking and talking that advance the inquiry process. Learning results from interactions among people and between people and their material and representational resources as they engage in inquiry. This article explores the role that multiple representations play in these interactions. Specifically, the paper reviews experimental and ethnographic studies conducted by our research group to:

- Establish the differences between the representational skills of expert scientists and novices.
- Show how expert scientists draw on these skills and the affordances of multiple representations to conduct their laboratory research.
- Contrast this with students' use of representations in the laboratory.
- Draw implications from this research for the design and use of representations and technology-based representational systems to support science learning.

Representational Competencies of Chemists and Students

In cognitive psychology, there is a long tradition of research that compares experts and novices to document similarities and differences in their cognitive structures and processes (Glaser & Chi, 1988). A common finding is that experts are able to cluster apparently dissimilar problems or situations into large meaningful groups based on underlying principles. For example, significant differences have been found in the cognitive structures of experts and novices in physics (Chi, Feltovich, & Glaser, 1981; Larkin, 1983; Larkin, McDermott, Simon, & Simon, 1980). In one task, expert physicists create large meaningful clusters of textbook physics problems based on underlying physics principles, such as "force problems" or "energy problems". Novices will organize their groups based on surface features, such as "pulley problems" or "inclined plane problems".

In our experimental research (Kozma & Russell, 1997), we found similar results using multimedia tasks. We also found some interesting extensions. We compared 11 professional chemists, faculty members, and graduate chemistry students (i.e., experts) and 10 college students taking general chemistry (i.e., novices) on two multimedia tasks. In the first task, subjects were individually asked to view 14 different computer displays, one after the other, in one of four representational forms: chemical equations, coordinate graphs, molecular-level animations, and video segments showing wet lab experiments. The subjects were given a set of 14 cards that corresponded to each of these displays. Strategic stills were used from those displays that were dynamic (e.g., animations, video segments). The subjects were then asked to group these cards into meaningful sets.

As in other studies, the expert chemists in this study were able to create large, chemically-meaningful clusters, significantly more so than novices. We also found that chemists used conceptual terms to label their clusters, terms such as “gas law,” “collision theory,” and so on. Furthermore, chemists tended to use a greater variety of representations in their groupings, three or four different kinds of representations compared with only one or two different types of representations used by novices (e.g., only graphs, or graphs and animations). Chemistry students labeled their groups using terms that merely described the surface features of the groups (e.g., “molecules moving about”, “concentrations changing with time”) and occasionally students merely named the type of representation (e.g., “graphs of concentrations”).

For the second task in our study, subjects were presented with a series of representations (the same as those in the first task) of chemical phenomena presented in one form and they were asked to transform each into another form of representation (e.g., transform an animation into a corresponding graph, a video of a reaction into an equation). Experts were significantly better than novices at transforming a given representation into a chemically meaningful representation in another form. They were particularly skilled at providing an appropriate linguistic transformation, or description, for a representation given in any other form, much more so than novices. That is, while chemists were more likely to give a description based on the underlying chemistry (e.g., “Heating shifts the equilibrium shown by color change.”), novices were more likely to merely describe the what they saw (e.g., “Heating causes the color change to get darker.”).

In summary, we found that novices used the surface features (such as color, motion, labels, etc.) of the displays to try to build an understanding of the chemical phenomena they represented. However, these features constrained their understanding, as well. That is unlike chemists, students were not able to easily cross the boundaries of different representations and connect them to create an understanding that went beyond the surface features of a given representational type. Chemists, on the other hand, were able to see displays with different surface features as all representing the same principle, concept, or chemical situation, and they were able to transform representations of a chemical concept or situation in one form into a different form. They easily moved across different representations and used them together to express their understanding of chemical phenomena.

While these experimental studies of expertise identify certain cognitive skills and abilities of scientific experts, the picture that they paint of scientific understanding is limited. As Dunbar (1997) points out, scientists studied in the psychological laboratory are often given contrived tasks of a brief duration, rather than authentic, complex, extended scientific problems. More importantly, subjects are studied in isolation, rather than in the social and physical contexts where science is conducted. “In vivo”, or ethnographic research, examines how scientists think and solve problems as they interact with colleagues and resources in their work situation, while they are engaged in authentic tasks. This kind of “in vivo” research on scientific practice can establish how social and physical resources foster and support the kinds of cognitive skills that scientists exhibit in “in vitro”, experimental studies.

Use of Representations by Chemists

In our subsequent research, we explored the relationship between the representational expertise of scientists and their use of these skills in their laboratories. We wanted to see how chemists use their ability to move fluidly and flexibly across different representations to help them conduct and understand their scientific investigations. We wanted to see how their ability to use scientific language helps them interact with other scientists engaged in similar practice. Conversely, we wanted to see how the features of representations afforded opportunities to discuss chemistry and advance shared understanding.

In our ethnographic research (Kozma, Chin, Russell, & Marx, 2000), we spent 64 hours observing and interviewing professional chemists in two chemical laboratories: one a laboratory in a pharmaceutical firm engaged in manufacturing marketable drugs; the other a university academic laboratory engaged in the synthesis of organic compounds.

The first thing we noticed was that representations were everywhere in these laboratories. Structural diagrams and equations were written on flasks and vials filled with compounds being heated, filtered, or waiting for reactions. They were written on glass hoods and white boards through out the lab. And they were in notebooks, reference books, and journal articles and advertisements on bookshelves and bench tops. There were also stacks of numeric and graphic output generated from NMR, mass spectrum, and other instruments that were used to measure reactions that were run. We analyzed the ways chemists used these various representations together to understand the chemical phenomena that are the object of their laboratory research. Two findings are particularly relevant to this review: Chemists used the material affordances of multiple representations to think about and conduct their investigations and they used the social affordances to argue for, explain, and justify their findings.

Material Resources That Support Thinking and Doing

One important use of representations by chemists was to help them think about the goals of their research and to reason about ways to accomplish those goals. This is illustrated in one of our observations in which James, a chemist in the pharmaceutical laboratory, was synthesizing a compound that would be used as a reference for an assay. As he described the compound he was trying to make, he spontaneously pulled out a pen and began drawing the structure of the molecule: “The thing I’m trying to make looks like this.” But in saying this, James was less concerned about the physical appearance of the product and more concerned about its underlying structure. Making a compound with the right structure is crucial to his work. This structure was better represented with a drawing than by a verbal description alone.

James went on to also draw a chemical equation that showed the reaction he was running in order to synthesize his intended compound. He explained:

> And so this is the nucleophile [*pointing to one of the structures on the reactant side of the equation*] and this is the electrophile [*pointing to the other structure*]. And what you get is sodium chloride [*a by-product of the reaction*]. But in my case that reaction [pointing to a flask] is just not going.

It is important to note that for James, there is a direct connection between the symbols he created and the physical materials on the bench in front of him. His pointing makes this connection explicit. The structures that he drew on paper corresponded to both the compounds in the flasks on his lab bench. These compounds are materials that can be seen. But the symbols also represented entities (e.g., nucleophiles and electrophiles) and processes (e.g., oxidation) that could not be seen, yet these entites and processes underlie and account for the observable phenomena. The representations that James drew gave material reality to these aperceptual entities and processes. The material features of the diagram—the letters and lines that stood for atoms and bonds—helped him think and talk in a different, particularly chemical way about what was happening with his investigations. As such, the representations also gave a chemical reality to material substances on the lab bench, substances that otherwise would be only colored liquids.

Representations also correspond to actions that chemists perform as part of their bench work and these actions have implications for both the material substances that chemists use (i.e., compounds) and the underlying aperceptual chemical entities (e.g., nucleophile) and processes (e.g., oxidation) that chemists think and talk about. James went on to say:

> J: And so this thing here [*he points to the flask*] that I'm filtering, I think it's yet another example of one of these that didn't go. I'm trying various things with the rest of this structure to activate this ring [*pointing to a benzene ring in a compound on the reactant side of the equation*] and see if, see if I can get it to go, but I, I'm not very hopeful at this point.

The "various things" that James tried were simultaneously different lab experiments and different symbols and symbolic operations. Chemists work with both of these forms simultaneously and seamlessly. James used the material results of his experiment and the representations together to try to understand why the experiment did not work and what he needed to do differently. He drew another set of equations that helped him think through a different, two-step procedure.

> J: What I did was to take this reagent and we're going to do it in two steps [*draws a second set of reaction diagrams*]. Take this guy [*points to a structure in the diagram*] which is not the oxidized

> sulfur now but sodium sulfothiophenol which is a much better nucleophile. And so then I'm, what I'm trying to do is to use this oxidation reaction [*gestures toward the diagram*] to get the sulfur to a sulfoxide. And so what, often times what you can't do in one step, you can do in two and it looks like that's [*points toward a flask on the lab bench*] going to work.

James continued to work back and forth between the specific symbolic features of the two equations (e.g., features representing potential reactive sites) and various experiments on the lab bench to ultimately find a reaction that produced the desired compound. Because he made a connection between the representations and the laboratory substances, the material resources of the diagrams (i.e., symbolic features) allowed him to think about alternative processes to perform on the chemical substances on his lab bench that accomplished his goal.

Resources that Support Social Interaction

Because James was working alone at the time, the fundamentally social nature of his use of representations was not apparent. Yet in his individual work, James recapitulated a social, rhetorical process that we observed in more overtly social contexts, as chemists worked together. In another session, we observed David and Tom working together in an academic laboratory. David ("D" in the protocol below) was the laboratory director and Tom (T) was his 2nd-year doctoral student. The discussion on which we draw began with David asking Tom to describe the results from the latest series of reactions he ran. Tom first drew the chemical structure of the starting reagents for a 2-step reaction on the whiteboard. Tom then drew an intermediate product and another reagent that he used to get the intended final product. He specified the amount of starting material and the yield from the first reaction. Then the task was to determine whether or not he had the intended product. Tom pulled out several NMR spectra that he had run on this compound.

This instrument-generated display also represents the structure of the compounds that chemists make. However, the display looks very different than structural diagrams of the sort that James generated to express the goals of his work. Instead of the letters and lines of structural diagrams that stand for atoms, bonds and their arrangements, an NMR spectrum consists of peaks of various heights arrayed in various clusters and positions along an X-Y graph. Chemists use the features of these instrument-generated representations to test, confirm, or refute the composition and structure of the compounds they synthesize. These instrument-generated representations do not make these confirmations on their own. The confirmation results from a coordination of the complex patterns of spectral peaks with the composition and arrangement of atoms, as displayed by a structural diagram. This is the social, rhetorical process that we observed between Tom and David.

Tom began to interpret the NMR spectrum. Some of the constituent atoms were easy to identify from the spectra ("Oh, yeah, it's definitely got tin in it."). Others were much more difficult to identify, as there was a possibility that the solution had one (or a mixture) of two isomers (i.e., compounds with the same atomic composition but different structural arrangements). David initially takes the position that they have a mixture of the two. Initially, Tom defers but begins to take a contrary position and makes a case that they have one particular isomer by identifying specific features of the NMR that support his position. As David works through the implications of Tom's argument, he spontaneously generates a diagram of the structure Tom proposed and uses the diagram to test the interpretation of the spectrum.

> D: Let's see [*looking at the spectrum*], so that would be uh, this compound here. So I got to write it out to think about it [*draws a diagram of Tom's hypothesized structure*] . . . OK. Well, uh, you got to keep the C-13 here. Uh, is this where you expect the amine to be [*points to a portion of the spectrum*]?
>
> T: Yes.
>
> D: Where would the thiocarbonyl be?
>
> T: Uh, I'll find out [*Tom pulls a reference book from the shelf*].

Here, David and Tom are coordinating symbolic features within and across multiple representations: the NMR spectra, a diagram, and a reference book. Through their interactions, they are connecting features of the structural diagram to those of the spectra. In using the instrument-generated spectra, they are connecting the hypothesized structure to the results of their experiments. In using the reference book, Tom is connecting their interpretation to the previous experiments of others in the chemistry community. However, the confirmation of the interpretation rests on the argument that David and Tom are able to build together using the materials they have assembled. In working through the analysis of the spectra, Tom finally builds a compelling case. David confirms this, again by referring to features of the representations.

> D: Oh, OK, so that's the C-methyl [*pointing to a peak on the spectrum*].
>
> T: Uh hum.
>
> D: So, 2.25 is probably good. Look at that [*points to another peak*], right where you would expect. S- methyl?
>
> T: C-methyl. You don't have a . . .
>
> D: Let me get this straight, if this is two [*refers to an area in the spectrum*], then the total of these three peaks would be six.
>
> T: Yes.

D: Sounds good to me. That's a very attractive explanation there.

This interaction more explicitly illustrates the way chemists use multiple representations to understand their work and it shows the social basis for this understanding. What began as a disagreement turned into a shared understanding, as David and Tom together coordinated multiple representations to identify the product of their investigation. This coordination depended on the ability of the chemists to map features of one representation onto those of another and to draw implications for the aperceptual composition and arrangement of atoms in the substances they synthesized in the laboratory. This activity is embedded in the everyday practice of laboratory chemists.

Use of Representations by Chemistry Students

The results of our ethnographic study of experts corroborate the findings of our experimental study. Experts are able to make connections across multiple representations and coordinate the features of these representations to support their discourse about the common chemical phenomenon that underlies them all. In our experimental study, students were not able to make these connections. How does this affect their thinking and talk in the laboratory?

To explore this question, we observed students in an undergraduate organic laboratory course (Kozma, 2000a). We observed four pairs of students as they worked during four laboratory sessions. Two of these sessions were particularly interesting because students worked with the same compound in both but the material and representational resources they had were very different. Because students could not make a connection across representations, this resulted in very different talking and thinking about chemistry.

In the first session, conducted in the wet lab, students synthesized dibenzalacetone in a two-step process. The second session was conducted in the computer laboratory using *Spartan*, a professional molecular modeling package. The software package allows users to construct a perspective drawing of a molecular structure, rotate it, measure the bond lengths and angles, and minimize the energy of the molecule. The students were directed to construct a molecular model of dibenzalacetone (the product that they had synthesized in the previous session) and compare its isomers. The intent of this activity was to have students determine which isomer of the compound they had synthesized in the previous wet lab session.

We video taped and coded the students’ interactions with each other, with their experiments, and with their teaching assistant for these two laboratory sessions. The two sets of sessions were similar in length and number of interactions. However, we found significant differences in the kinds of interactions. In the wet lab, students focused on the physical substances and procedures of their experiments; they rarely talked about substantive chemistry. When using computer-generated representations of structures, students are focused on underlying chemical entities and processes, much like chemists. However, students did not spontaneously connect the representations that they used in the computer laboratory with the materials and processes of their laboratory investigations, even though they were working with the same compound.

Focus on Physical Materials in the Wet Lab

In the wet lab, students had reagents, beakers, electric heaters, filters, and vacuum pumps. They also had a set of directions that guided their laboratory work in a step-by-step fashion. This situation and the resources that were available significantly affected what students and instructors did and said in the laboratory.

In our analysis of the interactions among students and between students and teachers, we found that the primary interaction in the web lab was help-seeking or help-giving. The largest number of these incidents involved students seeking help with equipment set up or experimental procedures from their TA, their partner, or students other than their partner. Students also sought help with the analysis of their results. However, this was not a deep analysis of their investigation; most often, this consisted of the student periodically asking the TA if their results were sufficient for the task (i.e., if their crystals were washed enough or dry enough).

An interaction that typified others between students and their TA was this one when Anna approached the TA to ask about one of the procedures.

> A: You know what these--when you add the 5 milliliters of water, are you supposed to stir the product and then the pH, or—‘cause . . .
>
> TA: You can do that if you want.
>
> A: ‘Cause it . . .
>
> TA: Don’t stir it too much, but just mix it up a little bit.
>
> A: ‘Cause it’s getting darker.
>
> TA: The product?
>
> A: Yeah, the pH is—the color is getting, like . . .
>
> TA: Okay, that’s ‘cause you probably didn’t stir it well enough at first. It’s not gonna get darker.
>
> A: Oh.

It is clear from our analysis that students in the wet lab were primarily focused on the physical-ness of the experiment: the material substances, the equipment, and the procedures. There was very little talk about substantive chemistry, either by the students or by instructors, as documented the interaction above. Only 3.1% of the incidents in the wet lab involved a discussion of substantive chemistry. Otherwise, the talk was almost exclusively about the physical material and procedural activities in the lab. In the example above, the focus of the talk between Anna and her TA was on the color of the solution and the correctness of the procedure; this was typical of most interactions. Neither student nor instructor talked about what was happening at a molecular level.

It is also important to note that neither Anna nor the TA drew representations of what was happening or what was intended. In fact, while diagrams and formulae appeared in students' formal lab reports, we never observed the spontaneous use of representations by students or TAs in the wet lab, unlike the practice we observed in our study of chemists. It seemed to be sufficient for both students and teachers to talk about the correctness of procedures and whether the color would change.

Focus on Underlying Chemistry in the Computer Lab

In the computer lab, each pair of students used the molecular modeling software to construct and manipulate a model of dibenzalacetone, the compound they had synthesized in the wet lab. The features of these representations supported students' conceptual talk. Specific features in the diagrams generated by the molecular modeling software (such as balls and lines) corresponded to particular structural elements within the molecule (such as atoms and bonds). Furthermore, students were able to computationally operate on these representations: rotate substructures and measure the distances between atoms and the angles within structures. These features and capabilities supported student discussion of corresponding chemical concepts such as the arrangement, shape and structure of a compound, talk that was very different than that in the wet lab.

In the following example, Anna (the same student as in the example above) is talking with Liz, her lab partner. They have just constructed a molecule and they have been directed by the lab manual to describe their molecule:

A: I'll just say one more thing and that's like, ah, about the lone pairs on the oxygen, single bonded oxygen. . . . The lone pairs on the oxygen—on the single bond, single bond, single bond oxygen, um, what do you call that? Um.

L: What do you want to say?

A: You know it pulls [*Anna makes to fists and pulls them apart to represent the forces she is trying to describe.*]. What do you call that? There is a term for it, when you have lone pairs and things, um, what she talked about in lecture, basically. The, um . . .

L: They're attracted to it?

A: Electronegative.

L: Oh dipole?

A: Dipole. She calls it dipole moment. High-dipole moment, maybe.

L: But so does the oxygen itself.

A: Yeah, but, look, if—if the double—if the lone pairs were not there [*Anna points to portion of the molecule on the screen with a pen and draws a line in the air to stand for the angle that the bond would be if the lone pairs were not there.*], then the oxygen, um, the hydrogen would be like differently.

As in the wet lab, the conversation of students is strongly influenced by the material resources available to them. However, in the wet lab, the resources were confined to equipment and physical substances. The resources were different in the computer lab. In this example, the specific features of the structural models (features such as balls, links, and angles) and functions of the software (such as the ability to rotate structures, measure angles and line lengths, etc.) shaped the chemical content of the students' conversations. The students talked not only about the depicted molecular structure but about other related concepts and terms, such as "dipole moment" and "lone pairs", that had been used in lecture but now had concrete manifestations. This conceptual chemical talk accounted for 57.4% of the interactions among students in this session, compared to 3.1% in the wet lab.

The use of these representations also increased the conceptual talk between students and TAs. Discussions with TAs moved from a focus on help-seeking related to procedure in the wet lab to concepts such as molecular shape, hydrogen bonding, and non-polar groups in the computer lab. TAs discussed chemistry concepts 18 times during our observations in the computer lab compared to only 1 time in the wet lab. These findings give evidence that specific features of representations can provide students and TAs with symbolic and procedural affordances that support conceptual discussion and the social construction of chemical understanding.

However, it is equally important to note what did not happen in the computer lab. We did not observe students or TAs making references in their talk to their wet lab experiments, even though the compound they were building and analyzing was the same compound they had synthesized in the wet lab during the previous session. In our observation of chemists (Kozma, et al, 2000), there was an integrated use of various representations and the phenomena they represented. Chemists in this study made explicit and implicit connections between their drawings and their experiments, as did James, or between drawings and spectra, as did David, and they used language to support these connections. Because of these connections, chemists could then reason with one representation (e.g., a structural drawing) and draw implications for another (e.g., a spectrum) or for the experiments they were running. The students that we observed in the organic laboratory course (Kozma, 2000a) did not make these connections and therefore they could not use one form to reason about another.

Nor did students in the computer lab use representations and their features to support their arguments. In fact, the activities in neither the computer lab or the wet lab in the organic course were structured in a way that evoked disagreement. In the chemistry laboratory of our ethnographic study (Kozma, et al., 2000), David and Tom disagreed over the interpretation of the spectra and whether they had synthesized the compound they intended. Their use of representations as rhetorical props was key to resolving their dispute. While there was description and perhaps explanation in the student discourse that we observed, there was no disagreement. This is due in large part to the fact that the experiments were preformulated and highly prescribed, unlike the investigations of scientists. So there is a relationship between the use of representations and the activity and social situations in which this use is embedded.

Design Principles for the Use of Multiple Representations

While a variety of representations are often used in science courses, several studies (Roth, Bowen, & McGinn, 1999; Bowen, Roth, & McGinn, 1999) have found that the representations used in science courses and science textbooks are not the same as those used by scientists nor are they used in the same way that scientists use them. While the use of language and representations is embedded in the everyday practice of scientists, students often use scientific words, equations, diagrams, and other symbolic resources apart from the scientific phenomena that they are meant to represent and apart from the scientific practices used to investigate these phenomena. As a consequence, students often see scientific symbol systems as a set of mental puzzles and, according to Krajcik (1991), “use the ‘correct’ words and apply formulas to obtain correct answers but lack understanding of the underlying chemical and physical concepts” (p. 119).

Carefully-designed representations embedded in authentic inquiry activities (Krajcik, et al., 1998) can provide students with the physical and social affordances that can support the scientific talk and understanding of students. The results of our research suggest three design principles that could increase these connections and support the learning of students:

- Have students use multiple, linked representations in the context of collaborative, authentic, laboratory investigations.
- Provide students with representational tools and symbolic systems that correspond to the entities and processes that underlie physical phenomena.
- Engage students in collaborative activities in which they generate representations and coordinate the features of representations to confirm and explain the findings of their scientific investigations.

Technology can play an important role in enabling these design principles. The symbolic and processing capabilities of computers (Kozma, 1991) can be particularly powerful, in this regard. In this remaining section, I review two software environments that our research group has designed over the years based on these principles (Russell & Kozma, 1994; Kozma, Russell, Jones, Marx, & Davis, 1996; Russell, Kozma, Jones, Wykoff, Marx, & Davis, 1997; Coleman, Kozma, Schank, & Coppola, 1998). One of the early environments that we developed, *4M:Chem*, implemented several design principles related to multiple-linked representations to support the development of chemical understanding and representational competence. Our current work, *ChemSense*, extends this to explicitly include elements of collaboration, rhetorical discourse, and epistemological thinking. Our goal with this work is use the material and social affordances of the system to foster chemical understanding, representational skill, and rhetorical discourse.

4M:Chem[2] used four different coordinated symbolic spaces to represent a chemical phenomenon that a student investigated within the system. These consisted of a chemical equation, a dynamic real-time graph, a molecular animation, and a video of a wet lab experiment (in lieu of a real experiment, as used in *ChemSense).* Students might begin a typical session by selecting an experiment, say "Equilibrium," and a chemical system, "N_2O_4/NO_2" for example, and manipulating certain parameters that correspond to their investigations (e.g., increase temperature, reduce pressure). The effects of their actions propagate through two or more simultaneously displayed multiple, linked representations.

We used color and the simultaneous onset of events as design conventions to link these different representations, such that objects and events in one representation corresponded to those in others. For example, NO_2 would be a reddish-brown gas in the video, the line of the graph would be labeled NO_2 is red, and the balls in the animation that represent NO_2 would also be red. As the N_2O_4 dissociated when heated, the system would become a dark red in the video window, the red partial pressure line for NO_2 would increase in the graph window, and the number of red-brown NO_2 molecules would increase in the animation window. As the reaction progressed, a new point of equilibrium would be reached, yet this new state would be represented differently in each window: The color would remain constant in the video window, the partial pressures would plateau in the graph window, and the molecules in the animation window would continue to move and react maintaining a constant ratio of products and reactants. Our intend was that these linked symbolic features would afford students and integrated understanding of equilibrium.

4M:Chem proved to be effective in early studies of its use in large chemistry lectures; students increased their understanding and reduced misconceptions (Kozma, et al. 1996). In a follow-up pilot study (Kozma, 2000b), we wanted to extend our research to look more closely at the material and social affordances of the environment. In this study, we asked students to work in pairs to conduct simulated experiments. We observed the discourse between two students ("Michael" and "Frank") as they used the environment to investigate an equilibrium system.

In brief, we found that at the beginning of the session, both students had a basic misconception, as measured by the pretest, that equilibrium was a static state in which the reaction came to a stop. We observed the process by which these students used the features of multiple representations together to modify their understanding of equilibrium. Through a series of interleaved questions, observations, and assertions, they moved from an inaccurate understanding to one that is more in line with scientific notions of chemical equilibrium. The features within and across these multiple, linked representations played an important role in supporting this advance.

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[2] Originally titled *4M:Chem*, this software is now being published under a different title: Russell, J.; Kozma, R.; Zohdy, M.; Susskind, T.; Becker, D. & Russell, C. (2000). *SMV:Chem (Simultaneous Multiple Representations in Chemistry)* [4 CD-ROM software set]. New York: John Wiley.

We first observed that the students took a specific surface feature of the graph (its intersection) to mean that the partial pressures are equal (an accurate interpretation) and inferred that at this point the system was at equilibrium (a scientifically inaccurate interpretation). One of the students, Michael, noticed a second surface feature of the graph, the leveling off or the plateau of the lines. These two prominent surface features of the graph—the crossing point and the plateau of the lines—supported the students' extended discussion of equilibrium and constrained the range of possible meanings of the graph and subsequently for the concept of equilibrium. By the end of the session, the students come to take plateau to mean equilibrium, rather than the crossing point.

How did this transformation come about and how did the representations support it? First of all, Michael interpreted a particular feature of the graph, "leveling off," as meaning "not changing." This created a dissonance between his understanding of equilibrium (expressed as "not moving" on the pretest) and the surface feature (the point where the lines cross) that both students had agreed was the point of equilibrium: Is equilibrium the crossing point or the plateau? The resolution of the graph's meaning was derived from a second representation, the video window. Michael noticed that at the crossing point of the graph, the color of the sample in the video was still changing. He used this to restate the problem to Frank and ask him for an interpretation of the graph. Frank resolved the issue by pointing to the plateau of the lines. Even though Michael was the person who raised the problem and noticed the feature in the video that led to the resolution of the issue, Frank served the important function of confirming the resolution by changing his interpretation. Later in the session, the students used the features of a third representation—the animation—to understand that at equilibrium the reaction continues, even though the color stops changing and the partial pressures have leveled off.

In these sessions, the interactions of Frank and Michael are much like those of David and Tom. David and Tom coordinate the features of the NMR spectrum and the diagram to converge toward a shared understanding of a property that underlies their investigation (e.g., the structure and arrangement of atoms in the substance they synthesized). Frank and Michael work back and forth between the features of the graph (e.g., the plateau of the graph) and those of the video (e.g., the stable color) and the animation (e.g., the continued reaction of the molecules) to converge on a shared meaning of an underlying chemical concept (i.e., equilibrium). This study illustrated the potential for multiple, linked representations to support discourse and the social construction of meaning. However, these interactions were not typical of those between students using *4M:Chem*. We felt we needed to refine our design.

With *ChemSense*[3], we extend the capabilities of the system in three ways:

- We provide generative tools that allow students to create representations of their understanding, not just observe representations created by others. These tools allow students to create their own molecular structures and animations of molecular reactions, thus supporting their thinking and talking about molecular-level entities and processes.

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[3] For additional information on *ChemSense* see www.chemsense.org.

- We connected the software environment to wet lab experiments, thus allowing students to consider representations of investigations they are conducting, rather than video segments of experiments conducted by others. Thus students can think and talk about the molecular-level entities and processes that account for the physical phenomena they observe.
- We scaffold the discourse of students to provide more support for the social use of representations. We apply knowledge-building principles proposed by Scardimalia and Bereiter (1994) to develop a discourse community of learners in chemistry.

We are currently analyzing data for two studies using *ChemSense*, one in a high school chemistry course and another in a university course. We believe this system will provide students with additional material and social affordances that will support the construction of shared understanding. The results of our studies will test this hypothesis.

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