Kozma, R. (2003). Material and social affordances of multiple representations for science understanding. *Learning and Instruction, 13*(2), 205-226.

The Material Features of Multiple Representations and their Cognitive and Social Affordances for Science Understanding

Robert Kozma
Center for Technology in Learning
SRI International

This article reviews experimental and naturalistic 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 features of multiple representations to support their shared understanding and laboratory practices and contrasts this with the way students use representations. Scientists coordinate features within and across multiple representations to reason about their research and negotiate shared understanding based on underlying entities and processes. Students, on the other hand, 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 afford 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 (this issue) 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 forms in long-term memory.

The research reported in this article takes a different perspective on multiple representations. It looks at the material features of external, multiple representations and the cognitive and social affordances they provide in support of science understanding. That is, it examines research on how scientists coordinate the symbolic elements 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.

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 and learning in terms of people's participation in practices of inquiry and discourse that include interactions with others and with the material, symbolic, and technological resources in their environment. The focus of this theory is on participation in processes that construct knowledge. These processes are shaped but not determined by the constraints and affordances of physical and social systems in which people interact. The affordances and constraints of physical or material systems—including equipment and representational systems—are those characteristics that permit or inhibit certain activities or cognitions that can be performed with the use of these systems. In the case of representations, this includes specific symbolic features and their arrangement and relationships within and across multiple forms or expressions. Similarly, the affordances and constraints of social systems shape activity and cognition and they include the conventions of social practice, such as patterns of turn-taking in conversation, appropriate ways to interact conversationally when working together on a task, and the kinds of products that are expected or warrants of claims that are required in order to decide that a kind of task has been successfully accomplished or satisfactory results obtained. In successful social systems, participants are attuned to constraints and affordances of both material systems and social practices, including the use of representations and the systems that they represent. Learning is characterized as becoming attuned to constraints and affordances of activity that results from interactions among people and between people and their material and representational resources as they engage in inquiry.

This article reviews several studies that together use mixed research methods to explore the ways expert and novice scientists use cognitive and social affordances that the material features of multiple representations afford. Specifically, the paper reviews the experimental and naturalistic studies conducted by our research group to:

- Establish the differences between the representational skills of expert chemists 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 a classroom laboratory.
- Draw implications from this research for the design and use of representations and technology-based representational systems to support science learning.
- Examine the influence that these designs have on student discourse and learning in a pilot situation.

Representational Skills 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 used a similar methodology to study the differences between experts and novices in their use of external representations of various sorts. Our findings were similar to those in the studies above. 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 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.

Mixed Methods in Multiple Studies

In our subsequent research, we conducted several naturalistic studies to complement our experimental study in what Tashakkori and Teddlie (1998) call “sequential mixed method design” and Cresswell (1995) calls a “two-phase design”. The advantages of this mixed approach and the findings of our studies as a collection are here. The methods and analyses of the individual studies are presented in more detailed in the original articles.

There are several advantages to using “mixed methodologies” within or across studies (Tashakkori & Teddlie, 1998: Creswell, 1995). One is the added internal validity or confidence in the relationships identified among variables that is achieved when findings are triangulated using different methodologies. The other is the added information and understanding that can be gained from methodologies that result in complementary findings. To achieve both advantages, we pursued the research questions in our experimental study of expert and novice scientists with two studies in naturalistic settings: professional chemistry laboratories and classroom laboratories.

While carefully controlled experimental studies in the cognitive laboratory can result in statistically reliable differences between experts and novices, the picture that they paint of scientific understanding is incomplete. As Dunbar (1997) points out, scientists studied in the cognitive 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 naturalistic 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 naturalistic study of scientific practice can corroborate experimental findings and help us understand how social and material resources foster and support the kinds of cognitive skills that scientists exhibit in “in vitro”, experimental studies. Naturalistic studies can also examine the differences between the tasks and situations in which experts and novices use these resources. This was the goal of our subsequent naturalistic studies: to reconfirm our experimental findings, to investigate the ways scientists (specifically chemists) and students use representations to understand science, and to explore the implication of these findings for the learning of science by students.

Use of Representations by Chemists

In one naturalistic research (Kozma, Chin, Russell, & Marx, 2000), we investigated 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.

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.

In sampling "in vivo" laboratory situations that addressed our research questions, we looked for those in which chemists used representations as part of their research. 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 and reference books, and in journal articles and advertisements on bookshelves and bench tops. There were also stacks of numeric and graphic output generated from NMRs (nuclear magnetic resonance spectrometers), mass spectrometers, and other instruments that were used to measure reactions that were run.

We observed and questioned researchers as they used representations. Field notes were taken, the sessions were audio recorded, and representations were collected. We analyzed the transcribed discourse and representation use, concentrating on the ways chemists drew on the material features of representations to understand their research findings and to interact with their colleagues. Three findings from this study are particularly relevant to this review. The first corroborates findings in our experimental study: chemists moved (sometimes easily, sometimes arduously) across different representations and used them together to understanding of chemical phenomena they studied. The other two findings illuminate this process: Chemists in this study coordinated the material affordances of representations within and across representations to think about and understand their investigations and they used the social affordances of these features to argue for, explain, and justify their findings.

Chemists use different representations for different purposes. For example, they use structural diagrams to reason about the composition and geometry of the compounds they try to synthesize in their laboratory experiments. They use chemical equations of the sort in Figure 1 to reason about and enact the procedures needed to synthesize their intended products. And they use the outputs of their laboratory instruments to confirm or disconfirm that the composition and structure of these products are those that they intended. The examples below show how chemists use the material features of these representations to support their thinking and their social discourse.

Figure 1 about here.

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 to us 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" (Figure 1). But in saying this and creating the drawing, James was less concerned about the physical appearance of the product and more concerned about its underlying structure. 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 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 entities 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—were affordances that James then used to think, act, and talk in a way that advanced his work. James went on to say:

> 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.

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 another flask on the lab bench*] going to work.

The symbolic expressions James used simultaneously represented both the physical materials—the solutions and procedures performed on the lab bench—and the underlying chemical entities and processes—compounds and their reactions. This corresponds to the findings of our experimental study (Kozma & Russell, 1997). But we can also elaborate on the earlier finding. Having made a connection between the representations and the laboratory substances, James used the material affordances of the diagrams (i.e., specific symbolic features) to think about different chemical structures and reactions that had implications for the procedures he performed on the chemical substances on his lab bench. The use of these representations and their material affordances supported the ultimate accomplishment of his goal.

Resources that Support Social Interaction

In another session, we observed David and Tom working together in an academic laboratory. As in our experimental study (Kozma & Russell, 1997), these chemists also made connections across features of different representations. In addition, this segment shows how chemists can use the social affordances of these features to argue for, explain, and justify the findings of their research.

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. The spontaneous drawing of a structural diagram and its use along with a NMR spectrum and diagrams in a reference book illustrate the ability that chemists have in coordinating multiple representations, as we observed in our experimental study (Kozma & Russell, 1997). But this segment also illustrates the rhetorical—and consequently social—nature of this coordination process and the role that the material features of the representations play in affording it. 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. Their mapping of the specific features of one representation onto those of another within this social context afforded the two chemists the ability to argue, persuade, and convince that may not have otherwise been available with only one representation or with only the physical substance.

Use of Representations by Chemistry Students

The results of our observational 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 entities and processes that underlie them all. In our experimental study, students were not able to make these connections. How does their use of representations affect student thinking and talk in the laboratory?

Naturalistic comparisons between students' use of representations in their laboratories with representational use by chemists in their laboratories are very difficult to make because in many ways the situations are quite different. For example, studies by Roth (Roth, Bowen, & McGinn, 1999; Bowen, Roth, & McGinn, 1999) document significant differences between the kinds of representations found in typical science courses with those used by professional scientists. Nonetheless, some interesting comparisons can be made, if the basis for comparison can be justified and the results appropriately contextualized. In our naturalistic study of chemistry students (Kozma 2000a), we observed students in an undergraduate organic laboratory course. As in the professional laboratories we observed, the tasks that students focused on were the synthesis of chemical compounds. They also used some of the same kinds of representations that chemists used. Furthermore, of the four laboratory sessions that we observed, we picked two sessions in which students were specifically tasked to conduct wet lab experiments and then analyze their products using representations. This served as the basis for our comparison. Given similarities between chemists and students in their general tasks—

synthesizing a compound and using representations to analyzing—what were the similarities and differences between them in their use of representations and their features to think and talk about their investigations?

We observed four pairs of students as they worked during these two sessions. 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 (i.e., compounds that have the same atomic composition but different structural arrangements). The intent of this activity was to have students determine which isomer they had synthesized in the previous wet lab session.

We videotaped and took field notes of the students' interactions with each other, with their experiments, and with their teaching assistant for these two laboratory sessions. The interactions were parsed into "incidents", coded according to the type of activity and the content of the discourse, and compared across the two sets of sessions. The sessions were similar in length and number of "incidents". But, we found important differences in the kinds of interactions between these two sessions and between the interactions of students and those of chemists.

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.

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. Out of 294 incidents recorded in the wet lab, 139 (47.3%) were coded as students seeking help, either from other students or from the instructor. Most of these incidents related to the set up or operation of equipment or procedures. This is evident in the segment above.

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. 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. This focus of students on the surface features of the chemical phenomena they studied corresponds to the finding in our experimental study (Kozma & Russell, 1997) that students are much more likely than chemists to base their thinking on surface features than underlying chemical principles. It is also important to note that neither Anna nor the TA drew representations of what was happening or what they intended to happen, in contrast to the spontaneous generation of representations by James and David, as they reasoned about their laboratory experiments in our naturalistic study (Kozma, et al., 2000).

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 (See Figure 2). 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 afforded students the ability to discuss corresponding chemical concepts such as the arrangement, shape and structure of a compound. In this way, their discourse was more like that of chemists than their discourse in their earlier wet lab session, although their talk is clearly less chemically sophisticated than that of professional chemists.

Figure 2 about here.

This point is illustrated in the following example, where 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.

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, as they engaged in the task of building and then explaining the structure of their compound. The students used these material features to talk about the depicted molecular structure and other related concepts and terms, such as "dipole moment" and "lone pairs", which had been used in lecture but now had concrete manifestations. This conceptual chemical talk accounted for 57.4% of the interactions among students in the computer laboratory session, compared to only 3.1% in the wet lab.

The use of these representations was also associated with more conceptual talk between students and TAs. Discussions with TAs shifted 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. In this way, the discussions of both students and TAs in the computer lab was more like that of chemists we observed in both our experimental (Kozma & Russell, 1997) and naturalistic studies (Kozma, et. al, 2000). The task for both Anna and Liz and David and Tom was to jointly explain the underlying composition and structure of the compound they had synthesized on the lab bench. In accomplishing their assignment, Anna and Liz used the physical features of the model to explain the shape of the molecule, much like David and Tom used the features of the NMR and their drawing to argue about the composition, structure, and identify of the material they synthesized.

However, it is equally important to note what did not happen in the computer lab. When we listened to the students and their TAs, we did not hear either make references to the materials they had synthesized in their wet lab experiments, even though the compound they built and analyzed with *Spartan* was the same compound they had synthesized on the lab bench during the previous session. In our observation of chemists (Kozma, et al, 2000), there was an integrated use of various representations and the physical 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. Students in our naturalistic study neither spontaneously generated representations to help them think about the physical substances they synthesized in terms of their underlying composition, nor did they connect the molecular models with the materials that they synthesized, even though they models supported their discussion of underlying chemical entities and processes. This lack of connection made by students among representations and between representations and phenomena corresponds to our findings in experimental study our experimental study (Kozma & Russell, 1997). Helping students to make these connections is a challenge to the effective use of multiple representations in support of science understanding. It is this challenge to which we turn next.

Design Principles for the Use of Multiple Representations

Is there a way to structure the use of multiple representations in laboratory courses so as to support student understanding of chemistry that is more like that of chemists? The results of our research suggest three design principles that could increase these connections and support the chemical understanding of students:

- Provide at least one representational system that has features that explicitly correspond to the entities and processes that underlie physical phenomena.
- Have students use multiple, linked representations in the context of collaborative, authentic, laboratory investigations.
- Engage students in collaborative activities in which they generate representations and coordinate the features of representations to confirm and explain the findings of their 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.

Related to the first principle, because novices rely on surface features and because there is often little about the surface of physical phenomena that reveals underlying scientific entities and processes, students should be provided with some representations should make these entities and processes explicit. Our observations of students using a chemical modeling package (Kozma 2000a) suggest that the materials features of representations can support student understanding if they correspond in some perceptual way to certain characteristics of abstract, scientific entities that do not otherwise have a concrete, visible character.

The aperceptual nature of underlying entities and processes is typical not only in chemistry but other sciences. Some representational features have already evolved for scientific entities in chemistry and other fields, entities such as “molecule”, “force”, “genotype”. Other representations can be designed. The symbolic capabilities of computers are particularly useful in giving material substance to such entities. The processing capabilities of computers can be used to enact relationships among these symbols in ways that given material substance to processes that underlie scientific phenomena. Arrows, balls, and other symbolic elements can be programmed to behave in ways that correspond to “oxidation”, “repulsion”, or “mutation”. For example, a velocity arrow can become longer or shorter, depending on the direction of acceleration. As a consequence, learners can manipulate these symbols, observe the consequences of their actions, and come to assign meaning to these symbols as they correspond to the underlying scientific concepts, such as acceleration. Several educational software environments have effectively implemented this design principle (Dede, Salzman, Loftin, & Ash, 2000; Horwitz & Christie, 2000; Kozma, 2000b; Roschelle, Kaput, & Stroup, 2000; White & Fredericksen, 2000).

Related to the second principle, experts use connections across different representations to construct meaning (Kozma & Russell; Kozma, et al., 2000) but novices have great difficulty making connections across representations and connecting representations to the physical phenomena they stand for. Instructional environments can scaffold these connections. Support for making these connections was not available in the professional modeling software that students used in our study. On the other hand, instructional software can provide students with tools to make connections cross multiple representations. Some of these representations, such as diagrams or equations, could be ones that students generate, much like those generated by James and David in our naturalistic study (Kozma, et al., 2000). Tools can be designed that support the creation of representations, particularly those with features that correspond to underlying entities and processes. Other representations may be generated by instruments connected to the physical phenomena, similar to the NMR spectra used by David and Tom. Increasingly-inexpensive sensors and probeware (such as pH meters, temperature probes, conductivity meters and so on) can connect representations (such as real-time graphs) to physical phenomena in the classroom laboratory. The representations generated by these instruments can support students' discussion of physical changes in terms of the features built into these displays, such as axes labeled pH and concentration, features that correspond to both physical observations and underlying principles (Kelly & Crawford, 1996).

The features of these multiple representations need to be linked, either by the instructional environment or/and by the students. Linkages can be accomplished by any of a variety of symbolic conventions that would allow students to map surface features of one representation onto those of another. For example, the actions that a student takes with one representation can correspond to certain outcomes in another representation. The number and relative location of symbolic entities could be the same in both representations, even though they may be represented differently otherwise. Another linking convention may be that the color of entities in one representation might be the same as those in another. The onset of an event in one representation could coincide with the onset of an event in another, and so on. Links can also be made through narration; a sound track can identify the connections between entities or events in one representation and those in another or a student can be asked to describe the links. Clearly, several of these linkage mechanisms can be used together in a reinforcing way. Several software systems have implemented one or more of these conventions (Horwitz & Christie, 2000; Kozma, 2000b; Roschelle, Kaput, & Stroup, 2000; White & Fredericksen, 2000)

Finally, related to the third principle, instructional tools and tasks can be designed to support the collaborative efforts of students as they conduct and explain their investigations. Our study of students in the laboratory (Kozma 2000a) and the studies of others (Roth, Bowen, & McGinn, 1999; Bowen, Roth, & McGinn, 1999) confirm that the representations used in science courses and science textbooks are often disconnected from authentic scientific phenomena and practices. 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 of students. From the situative perspective, science learning occurs through a series of interleaved assertions, gestures, actions, acknowledgments, requests for clarification, explanations, elaborations, and other linguistic devices for signaling agreement and fixing troubles in shared understanding (Pea, 1992, 1993, 1994). Through this discourse, interlocutors may converge on shared meaning that is more than either understood in the beginning (Roschelle, 1992), as illustrated by David and Tom in the professional chemistry laboratory. Representations and technological environments can structure and augment these learning conversations for students (Pea, 1992, 1993, 1994). First, technological environments can be designed to provide students with symbolic features, as described above, that enable them to make connections across representations (as scientists do) and coordinate these features to create a deeper understanding of the phenomena. Second, instructional tasks can be designed to structure students' use of these environments to argue about, question, explain, and the convergence toward shared understanding (Scardamalia & Bereiter, 1994; Brown, Campione, & Jay, 1993), an understanding based on underlying conceptual entities and processes.

Students' Use of Multiple-Linked Representations: A Pilot Study

We have applied these design principles to build software environments that help students understand concepts and principles in chemistry (Russell & Kozma, 1994; Kozma, Russell, Jones, Marx, & Davis, 1996; Russell, Kozma, Jones, Wykoff, Marx, & Davis, 1997; Schank, & Kozma, in preparation). We implemented several of these design principles in one of the early environments that we developed to support the development of chemical understanding, *4M:Chem* (now marketed as *SMV:Chem*; Russell, et al., 2000). Our current work, *ChemSense* (http://chemsense.org/), extends this earlier design to explicitly include the generation of multiple representations by students as they explain the results of their collaborative investigations (Schank & Kozma, in preparation).

While *ChemSense* is still in its early stages, a pilot study (Kozma, 2000b) using *4M:Chem* illustrates the effectiveness of these design principles, as they are embedded in a technological environment. *4M:Chem* uses four different but coordinated symbolic spaces to represent a chemical phenomenon that a student is investigating. These consist 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 (see Figure 3).

Figure 3 about here.

We use color and the simultaneous onset of events as design conventions to link these different representations, such that objects and events in one representation correspond to those in others. For example, NO_2 is a reddish-brown gas in the video, the line of the graph labeled NO_2 is red, and the balls in the animation that represent NO_2 are also red. As the N_2O_4 dissociates when heated, the system becomes a dark red in the video window, the red partial pressure line for NO_2 increases in the graph window, and the number of red-brown NO_2 molecules increases in the animation window. As the reaction progresses, a new point of equilibrium is reached, yet this new state is represented differently in each window. The color remains constant in the video window, the partial pressures plateau in the graph window, and the molecules in the animation window continue to move and react maintaining a constant ratio of products and reactants. The intended consequence of using this system is that students will come to understand equilibrium as an integration of the surface features across these multiple linked representations. This system proved to be effective in early studies of its use in large chemistry lectures (Kozma, et al. 1996).

In a pilot study (Kozma, 2000b), we wanted to extend our work 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. A manual guided their work and asked them to make predictions, record observations, give explanations, and draw conclusions. They were asked to come to some agreement, if possible, in recording their answers. If students disagree, they are instructed to try and convince each other of their position, using whatever evidence was available. The following protocol illustrates the results in one pair of students.

The two male students, Frank and Michael (F and M) were enrolled in an introductory chemistry course and volunteered for the study. Both of the students began the session with significant misconceptions about chemical systems at equilibrium. Frank defined equilibrium as when "the chemical reaction has taken place and at this point there is no further change." Michael defined it as "the point at which a chemical reaction does not move either way." At the end of the session, both students showed a deeper understanding of chemical equilibrium. Frank defined equilibrium as "The point [at which] the reactions have stabilized and the changes are constant." Michael defined equilibrium as "The point at which the reaction moves both ways equally. There is no net movement backward or forward." In addition, while both students drew diagrams of equilibrium reactions that showed only products on the pre-test, their post-test diagrams showed that all species were present at equilibrium.

While viewing the representations and discussing the observations and responses to the manual, students made verbal and physical references to specific features of representations and that these features shaped their thinking and talk. For example, at one point while viewing the graph of the cooling experiment, Frank says: "Equilibrium? Like equilibrium is right there, or something?" [*points to the intersection of the lines in the graph*]. Through his pointing, Frank is expressing a misconception that we found in our earlier research (Kozma et. al., 1990), that at equilibrium, the partial pressures or concentrations of reactants and products are equal (what we described in our research as the "EQUALibrium" misconception). This misconception is supported by a feature of this particular representation: the lines of the two reactants cross when the partial pressures are equal (although, this is not the point at which the system is at equilibrium).

However, as a result of their interaction with each other and with multiple representations, Frank and Michael both come to have a correct understanding of equilibrium. In the following protocol, we examine how the students achieved this understanding through their interaction with each other and the affordances of the software. At the point where we pick up the conversation, the students have run the experiment with the video window, the graph window, and the equation window open. The students are responding to the question in the manual that reads: **Describe what you observe in the graph window**.

M: The concentrations crossed at equilibrium. Actually, is that crossing at equilibrium. Or is it just . . .

F: Reaching it.

M: Well, I mean, actually, equilibrium . . . isn't it just . . . is equilibrium where they reach the same concentrations or is it where they kind of have the same . . . Because they don't change, like after while they level off.

F: I thought it was when there's- where from the graph is when there's the same amount of N_2O_4 and NO_2, see? [*AR points to the crossing lines in the graph*] They cross and that means they have the same . . . the pressure was the same. The same pressure.

M: So, what does that say about equilibrium?

F: Well, at equilibrium they should both exchange, like go back and forth like on the animation thing at the same rate.

M: [*MN reruns the experiment*] All right. Well? Okay, so now the cooling sample already passed [*MN points to the point at which the lines cross in the graph*]. It's still darker [*MN points to the vial of NO_2 in the video*].

M: Oh, duh, actually, it's not gonna be the same concentration, is it, because there's two of these, there's only one of these [*MN points to the subscripts of each species in the equation*]. Okay.

F: So, it should be darker?

M: So, is this equilibrium right here [*MN traces the plateau of the

NO_2line in the graph] then? Or is this [*He points to the intersection of the lines*]?

F: Equilibrium should be where the pressures keep constant [*AR points to the right side of the graph where the lines plateau*]**.**

M: Okay. So it's going to be right here [*MN traces the plateau of the NO_2line*], then?

F: So maybe it's at five minutes and not where they cross?

M: All right.

This brief segment of discourse shows a significant transformation in the meaning that Michael and Frank assign to specific features of the representations and in their understanding of equilibrium. At the beginning, both students had a basic misconception about equilibrium as a static state, as measured by the pretest. The students take a particular surface feature of the graph (its intersection) to mean that the partial pressures are equal (an accurate interpretation) and that at this point the system reaches equilibrium (a scientifically inaccurate interpretation). Michael notices 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—support the students' extended discussion of equilibrium and constrain the range of possible meanings that they have for the graph and subsequently for this concept. By the end of the segment, the students come to take plateau to mean equilibrium, rather than the crossing point.

How does this transformation come about? First of all, Michael interprets a particular feature of the graph, "leveling off," as meaning "not changing." This creates 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 agreed was the point of equilibrium, prior to the above segment. Is equilibrium the crossing point or the plateau? With Michael's expression of his confusion to Frank, it becomes part of their joint activity and Frank becomes involved in resolving the meaning of the graph, even though he had not noticed the second surface feature and was satisfied with his original interpretation of the graph.

The source of resolution of the graph's meaning is a second representation, the video window. Michael reruns the experiment and notices that at the crossing point of the graph, the color of the sample in the video is still changing. He uses this to restate the problem to Frank and ask again for an interpretation of the graph. Frank resolves the issue by pointing to the plateau of the lines. Even though Michael is the person that raised the problem and notices the feature in the video that leads to the resolution of the issue, Frank—the person who was satisfied with the original interpretation—serves the important function of confirming the resolution by changing his interpretation. In subsequent interactions during this session, the students make references to the animation and extend their understanding to include the dynamic nature of reactions at equilibrium.

In this protocol, the interactions of Frank and Michael are much like those of David and Tom in our naturalistic study of chemists (Kozma, et al., 2000). 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) to converge on a shared meaning of an underlying chemical concept (e.g., equilibrium).

Conclusions

This article reviewed studies that used mixed experimental and naturalistic methodologies to study the use of representations by scientists and science students. More specifically, it examined the material features of multiple representations, and their cognitive and social affordances to support science understanding. It began by describing the representational competencies of expert scientists, as displayed on cognitive tasks in experimental study, and contrasting these skills with those of students. It went on to show how scientists used representations in the natural settings of their own research laboratories to understand scientific phenomena. Scientists are very skilled at flexibly and fluidly moving across multiple representations based on underlying principles. They use the features of various representations, individually and together, to think about the goals and strategies of their investigations and to negotiate a shared understanding of underlying entities and processes. Novices are less skilled in the use of representations and rely on their surface features for meaning. The students we studied had difficulty making connections between representations and the phenomena they stand for and making connections across the features of multiple representations to understand scientific phenomena in terms of underlying entities and principles. Nonetheless, the use of certain representations (i.e., molecular models) with features that corresponded to underlying entities and structures increased student discourse about substantive chemistry.

The article discussed the implications that these findings have for the design of instructional environments that use multiple, linked representations in support of collaborative investigations. A pilot study showed how a pair of students using such a system engaged in extended discourse to construct shared meaning out of surface features across multiple linked representations. In this way, they both achieved a scientific understanding of the entities and processes that underlie a scientific phenomenon and they replicated the discourse practices of scientists. The results of this research demonstrate the potential that technology has to support student thinking and to augment student discourse. The results of our pilot study suggest that the use of these symbolic environments along with investigative laboratory activities can provide cognitive and social affordances that support the construction of shared understanding of scientific phenomena.

Acknowledgements

This paper was written with the support of a grant from the National Science Foundation #REC-9814653.

References

Bowen, G., Roth, W. M., & McGinn, M. (1999). Interpretations of graphs by university biology students and practicing scientists: Toward a social practice view of scientific representation practices. *Journal of Research in Science Teaching, 36*(9), 1020-1043.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*, 32-42.

Brown, A., Campione, J., & Jay, M. (1993). Computers in a community of learners. In E. De Corte, M. Linn, H. Mandl, & L. Verschaffel (Eds.), *Computer-based learning environments and problem solving* (pp. 163-188.). Berlin: Springer-Verlag.

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

Creswell, J. (1995). *Research design: Qualitative and quantitative approaches*. Thousand Oaks, CA: Sage.

Dede, C., Salzman, M., Loftin, B., & Ash, K. (2000). The design of immersive virtual learning environments: Fostering deep understandings of complex scientific knowledge. In M. Jacobson & R. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 361-414). Mahwah, NJ: Erlbaum.

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

Glaser, R. & Chi, M. (1988). Overview. In M. Chi, R. Glaser, & M. Farr (Eds.), *The nature of expertise* (pp. xv-xxviii). Hillsdale, NJ: Erlbaum.

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

Horwitz, P. & Christie, M. (2000). Computer-based manipulatives for teaching scientific reasoning: An example. In M. Jacobson & R. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 163-192). Mahwah, NJ: Erlbaum.

Kelly, G. & Crawford, T. (1996). Students' interaction with computer representations: Analysis of discourse in laboratory groups. *Journal of Research in Science Teaching, 33*(7), 693-707.

Kozma, R.B. (1991). "Learning with media." *Review of Educational Research*, *61*(2), 179-212.

Kozma, R. (2000a). Students collaborating with computer models and physical experiments. In C. Hoadley (Ed.), *Computer support for collaborative learning* (pp. 314-322). Mahwah, NJ: Erlbaum.

Kozma, R. (2000b). The use of multiple representations and the social construction of understanding in chemistry. In M. Jacobson & R. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 11-46). Mahwah, NJ: Erlbaum.

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

Kozma, R. & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 43*(9), 949-968.

Kozma, R., Russell, J., Johnston, J., & Dershimer, C. (1990). *College students' understanding of chemical equilibrium*. A paper presented at the Annual Meeting of the American Educational Research Association, Boston, MA.

Kozma, R.B., Russell, J., Jones, T., Marx, N., & Davis, J. (1996). The use of multiple, linked representations to facilitate science understanding. In S. Vosniadou, R. Glaser, E. De Corte, & H. Mandel (Eds.), *International perspective on the psychological foundations of technology-based learning environments* (pp. 41-60). Hillsdale, NJ: Erlbaum.

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

Larkin, J. (1983). The role of problem representation in physics. In D. Gentner and A. Stevens (Eds.), *Mental models* (pp. 75-98). Hillsdale, NJ: Erlbaum.

Larkin, J., McDermott, J., Simon, D., & Simon, H. (1980). Expert and novice performance in solving physics problems. *Science*, *208*, 1335-1342.

Mayer, R. (this volume).

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

Pea, R. (1993). Learning scientific concepts through material and social activities: conversational analysis meets conceptual change. *Educational Psychologist, 28*(3), 265-277.

Pea, R. (1994). Seeing what we build together: Distributed multimedia learning environments for transformative communications. *Journal of the Learning Sciences, 3*(3), 285-299.

Resnick, L. (1988). Learning in school and out. *Educational Researcher. 16*(9), 13-20.

Roschelle, J. (1992). Learning by collaborating: Convergent conceptual change. *Journal of the Learning Sciences, 2*(3), 235-276.

Roschelle, J., Kaput, J., & Stroup, W. (2000). SimCalc: Accelerating students' engagement with the mathematics of change. In M. Jacobson & R. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 47-76). Mahwah, NJ: Erlbaum.

Roth, W. M., Bowen, G. M. & McGinn, M. (1999). Differences in graph-related practices between high school biology textbooks and scientific ecology journals. *Journal of Research in Science Teaching, 36*(9), 977-1019.

Roth, W. M., & McGinn, M. (1998). Inscriptions: Toward a theory of representing as social practice. *Review of Educational Research, 68*(1), 35-59.

Russell, J., & Kozma, R. (1994). 4M:Chem - Multimedia and Mental Models in Chemistry. *Journal of Chemical Education, 71*(669-670).

Russell, J., Kozma, R., Jones, T., Wykoff, J., Marx, N., & Davis, J. (1997). Use of simultaneous-synchronized macroscopic, microscopic, and symbolic representations to enhance the teaching and learning of chemical concepts. *Journal of Chemical Education, 74*(3), 330-334.

Russell, J.; Kozma, R.; Zohdy, M.; Susskind, T.; Becker, D. & Russell, C. (2000). *SMV:Chem (Simultaneous Multiple Representations in Chemistry)* [software]. New York: John Wiley.

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

Schank, P. & Kozma, R. (in preparation). *Learning chemistry through the use of a collaborative, representation-based knowledge building environment.*

Schnotz, W. & Kulhavy, R. (1994). *Comprehension of graphics.* Amsterdam: North-Holland.

Tashakkori, A., & Teddlie, C. (1998). *Mixed methologoy: Combining qualitative and quantitative approaches*. Thousand Oaks, CA: Sage.

Van Sommeren, M., Reimann, P., Boshuizen, H. & de Jong, T. (1998). *Learning with multiple representations*. Amsterdam: Pergamon.

White, B. & Fredericksen, J. (2000). Technological tools and instructional approaches for making scientific inquiry accessible to all. In M. Jacobson & R. Kozma (Eds.), *Innovations in science and mathematics education: Advanced designs for technologies of learning* (pp. 321-360). Mahwah, NJ: Erlbaum.

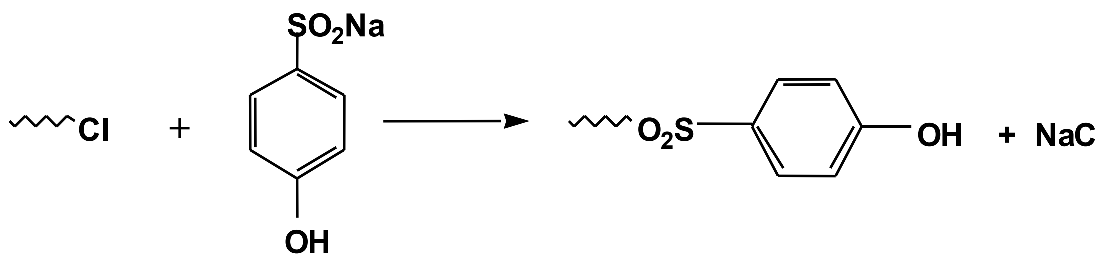

Figure 1. Chemical equation constructed by James to explain his work.

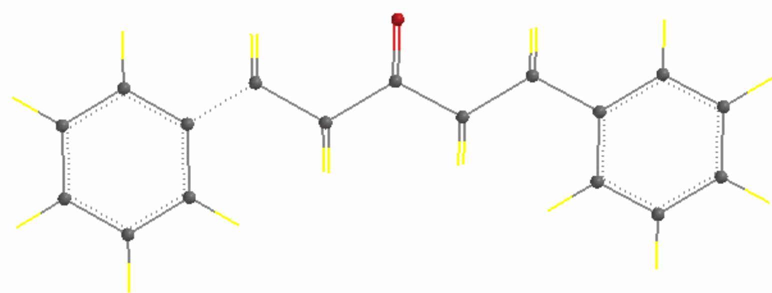

Figure 2. A student molecular model of dibenzalacetone using *Spartan.*

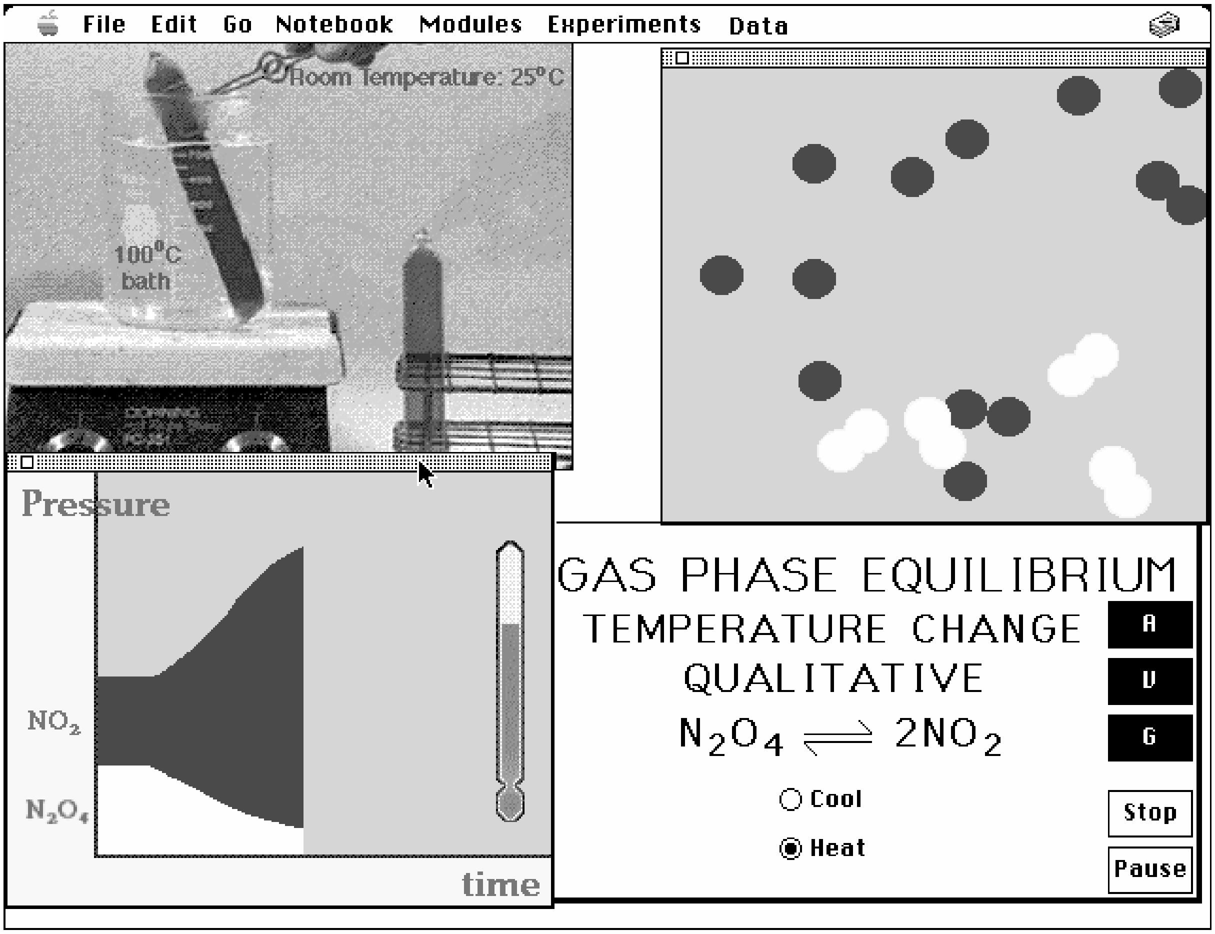

Figure 3. Screen shot from *4M:Chem*.