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The Use of Multiple Representations and the Social Construction of Understanding in Chemistry

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THE IMPORTANCE OF REPRESENTATION IN SCIENCE

Much that is of interest to the scientific community are phenomena that exist at scales beyond our temporal, perceptual, or experiential limits. Whether the phenomenon is cosmological, geological, biological, or chemical, our window on the world is really very small. For example, it is estimated that the universe has taken 15 billion years to evolve to its current state from the primordial Big Bang. It has taken the Earth's surface about 200 million years to form the current continents from the supercontinent Pangaea. Our early huminid ancestors began their distinct evolutionary path about 7.5 million years ago. Obviously, changes on these temporal scales are not directly accessible to us within a life time of 70-

some years, yet understanding changes of these magnitudes is the motivation for many important lines of scientific research.

Even within more contemporary time frames, our access to scientific phenomena is limited by our perceptual mechanisms. For example, we see light waves in the range between 400 nm (violet) to 700 nm (red). Many substances absorb light energy within this range and reflect complementary wave lengths that enable us to see them. However, many other substances either do not absorb light energy or do so at wavelengths beyond this range and thus they are invisible to us.

Size and distance also present formidable challenges to direct perception. Even with optical magnification, it is physically impossible for us to see anything smaller than 2×10^{-5} cm, yet the largest atoms are about 5.0×10^{-8} cm in diameter; the diameter of the smallest atom, hydrogen, is 6.4×10^{-9} cm. At the other extreme, the Universe is about 10 billion light years across and expanding at the relative rate of 50 kilometers per second per megaparsec. However, the furthest astronomical object that we can see with the naked eye is M 31, the Andromeda Galaxy, which is only about 2.5 million light years away from us.

Expansion of the universe, tectonic plate drift, evolution of species, and molecular structure and reactivity are all scientific phenomena that are not available to direct experience. Yet, understanding these phenomena is crucial to the development of scientific knowledge. Science in the 21st Century will be even less accessible to our direct perceptions and actions as we push the boundaries of current knowledge.

Consequently, our understanding of scientific phenomena will be increasingly dependent on our ability to access and interact with them indirectly. Currently, much of what scientists understand is derived from physical signs, frequently mediated by instruments of some sort, such as the red spectral shift of moving galaxies, sonar mapping of the undersea volcanic ridges that separate continents, carbon-13 dating of skeletal remains, genetic comparisons across species, and NMR spectra of molecular structures. Our understanding is further mediated by the symbolic expressions created to represent these phenomena, such as verbal descriptions, numerical equations, coordinate graphs, structural diagrams, and so on.

Tools and symbol systems have played an important role in the development of science. Historically, significant progress in scientific understanding has been associated with the introduction of new tools or instruments that allowed scientists to go beyond their experiential and perceptual limitations. Progress has also been associated with the creation of new representational forms that allowed scientists to think and communicate differently about scientific phenomena. In chemistry, for example, the perceptual inability to distinguish among invisible gases impeded the understanding of pneumatic chemistry, as well as that of other more visible chemical phenomena, such as combustion and acidity, until the late 18th Century (Brock, 1992; Partington, 1989). The invention of the pneumatic trough, eudiometer, gasometer, combustion globe, and ice calorimeter, used with the earlier technology of the balance, allowed 18th Century chemists to isolate gases and collect precise quantitative data about these invisible substances. Lavoisier combined the ability to separate chemical substances with a new way of representing them—a new nomenclature and symbol system—to bring about a revolution in chemical thought by focusing on the imperceptible, elemental composition of substances. In creating new representational forms, Lavoisier moved the discipline of chemistry beyond a science of substances to the modern science of molecular composition and structure.

Goals of the Chapter

The focus of this chapter is on the inherently representational nature of scientific understanding and the development of new ways of representing science that support this process, particularly ways that support student learning. I examine the role that representations play in science and the expertise that scientists have developed in using representations to do their work and understand scientific phenomena. By way of contrast, I examine the difficulty that students have in understanding science and in using scientific representations.

A central theme of the chapter is the ways that technology can augment the cognitive and social processes of scientific understanding and learning. I discuss design principles for such technological environments that use the surface features of representations to help students understand deep, underlying scientific principles. I examine a particular software application in chemistry—MultiMedia and Mental Models in Chemistry or 4M:Chem—that implements these principles; and I evaluate the impact it has on student understanding. The chapter ends by extending this discussion to show how students can interact with each other and with the computer software to socially construct an understanding of chemical phenomenon.

REPRESENTATION AND EXPERTISE

Representations and Scientific Expertise in Chemistry

Creating an understanding from signs and symbols is much of what scientists do. This is often an arduous and effortful activity. For example, in our ethnographic study in industrial and academic chemical laboratories (Kozma, Chin, Russell, & Marx, 1997), we observed chemists working individually and together using a range of signs and symbols to understand the results of their syntheses. Among the signs they used were the colored traces of thin layer and column chromatography and the characteristic arrangement, shape, and clustering of peaks on the print outs of mass and nuclear magnetic resonance (NMR) spectroscopy. The symbolic representations that these chemists created include structural diagrams, equations, and chemical formulae.

The chemists in our study used these various signs and representations to converge on an understanding of the scientific phenomena that were the objects of their research. We observed chemists moving back and forth between these symbols and signs, for example, between the structural diagrams of target compounds and NMR spectra of their results, to speculate on the composition and structure of the products they had synthesized. Sometimes they used the features of diagrams to generate hypotheses about the structure of compounds and then confirm or reject these by examining the clustering and position of spectral peaks; other times their interpretation of specific features of spectra would be aided by sketching out a diagram that might explain them. Sometimes they would confirm that they had synthesized their desired products; at other times they would find that they had not and they would go back and take the experiment in a different direction. The chemists would at times agree on the interpretation of signs and representations; while on other occasions, they would deliberate and disagree.

In this way, the chemists of our study were much like the researchers in a genetics laboratory studied by Amman and Knorr-Cetina (1990). Scientists in this laboratory gathered around recently exposed X-ray films of DNA or RNA fragments. As they examined the film, they pointed, made verbal references to marks on the film, drew inferences, raised objections, asked questions, returned to the film, provided replies, and so on until a conclusion, but not necessarily consensus, was reached. This socially constructed sense of "what was seen" was reproduced when the data were transformed into evidence that appeared in scientific papers or oral presentations. These observations and those of our ethnographic study confirm the unsettled, problematic, fallible, human social activity of “science in the making” or “science of the unknown” (Latour, 1987; Lemke, 1990) and the role that representations play in this negotiated process.

These findings also suggest an integral relationship between the signs and symbols of a science and the understanding that scientists have of their domain. The use and understanding of a range of representations is not only a significant part of what chemists do—in a profound sense it is chemistry. Perhaps that is why chemists are so skilled at using multiple representations. In our experimental laboratory (Kozma & Russell, 1997), we found significant differences between expert and novice chemists in their ability to create an understanding of chemistry using a variety of representational forms, particularly language. In this study, we gave practicing chemists (i.e., experts) and college chemistry students (i.e., novices) two multimedia cognitive tasks. In the first task, subjects were asked to view a number of computer displays in one of four representational forms (graphs, molecular-level animations, chemical equations, and video segments of experiments) and group these displays into meaningful sets. As in other studies of expertise (Glaser, 1989; Glaser & Chi, 1988), our expert chemists were able to create large, chemically meaningful clusters. In doing so, experts frequently used three or four different kinds of representations to create their groups. In addition, experts used conceptual terms to describe or label their clusters, terms such as "gas law," "collision theory," and so on.

For the second task in our study, subjects were asked to view a series of representations of chemical phenomena presented in one form and to transform each into another form (e.g., transform an animation into a corresponding graph, a video of a reaction into an equation). Experts were much more able than novices to transform any 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.

The results of our laboratory study of representational expertise in chemistry corresponds to those in other scientific domains, such as climatology

(Lowe, 1993) and biology (Kindfield, 1993/94). For example, Lowe found that meteorologists were much more able to accurately reconstruct a weather map from memory than were non-meteorologists. Perhaps more significant is how experts and non-experts differed in the strategies they used to recall the elements of the weather map. Meteorologists recalled elements in patterns based on underlying meteorological principles; non-meteorologists recalled elements based on the similarities of their surface features. Kindfield compared biologists with more or less advanced training in genetics in their spontaneous use of diagrams to reason about sub-cellular biological processes. She found that geneticists used their diagrams in a flexible way to help them think through the immediate reasoning task. Their diagrams, in turn, cued relevant knowledge that was used to solve the problem. Undergraduate biology students, on the other hand, used diagrams in a rigid way and could not map them onto the problem they were trying to solve. Kindfield takes these findings as evidence that advanced representational skills and conceptual knowledge co-evolve or mutually influence one another in the development of understanding of a scientific phenomena, a position supported by the findings from our studies.

In summary, experts are able to use a range of signs and symbols to create an understanding of scientific phenomena. They move fluidly back and forth between representations and use them together to solve problems. Furthermore, these representations are used within a community of other scientists to state hypotheses, make claims, draw inferences, ask questions, raise objections, and reach conclusions.

Representation and the Understanding of Novices

While chemists in our laboratory study (Kozma & Russell, 1997) demonstrated their expertise in the use of various representations, novices lacked both the underlying knowledge of chemists and their representational skills. While the expert chemists were able to create large clusters, the novices created significantly smaller clusters. While the experts used three or four different representations to create their groups, the groups composed by novices more often included only one or two different types of representations. While the experts used conceptual terms to describe their clusters, the descriptions of novices were more often based on the surface features of the representations in the cluster, features such as color, objects depicted, graph labels, and types of representations (e.g., "red molecules bouncing around," "graphs of pressure and concentration," etc.). Finally, novices were much less able than experts to transform a given representation into another form. In brief, while experts were able to use their deep conceptual understanding and their representational skill to create chemically meaningful clusters that connected different representational forms, the understanding of novices was more dependent on and bounded by the surface features of particular representations and they could not connect chemical phenomena represented in one form to the same ones represented in another form.

The reliance of novices on the surface features severely impedes their ability to understand scientific phenomena and reason about them. First, students' understanding is often constrained by the physical aspects of a scientific phenomena; and there is frequently little about these surface features that correspond to underlying chemical entities or processes. For example, when Krajcik (1991) interviewed 9th grade students and asked them to draw how the air in a flask would appear if they could see it through a very powerful magnifying glass. A large majority of the students did not draw air as composed of tiny particles; rather, they simply drew wavy lines to represent the air in the flask. Similarly, Nakhleh (1992) found that 11th grade students who had completed a unit on acids and bases drew waves, bubbles, or shiny patches when asked to draw how an acid or base would appear under a very powerful magnifying glass. In these studies, students could not move beyond the surface features of the physical phenomena to develop an understanding of the underlying chemical entities and processes.

Second, novice understanding seems to be constrained by the surface features of symbol systems and symbolic expressions used to represent science. Unfortunately, there is little about the surface of these symbols that corresponds to the underlying chemistry concepts. Nor do students have the representational competence to make the mappings from symbols to these abstractions. Consequently, scientific symbols often do not help and frequently interfer with students' understanding of chemistry. For example, in a study by Kozma, Russell, Johnston, and Dershimer (1990), college students had a variety of misconceptions about chemical equilibrium that corresponded to the symbol systems that they used. Many students had the notion that at equilibrium, chemical reactions stop. There is nothing about the surface features of the symbol used to represent equilibrium (i.e., $<=>$) that would convey its underlying dynamic nature. In a study by Yarroch (1985), high school chemistry students were interviewed on the meaning of chemical equations. Even though they were able to balance chemical equations, most students had little understanding of the chemical meaning of these symbols. They were not able to differentiate between subscripts and coefficients in the chemical equation $N_2 + 3H_2 \longrightarrow 2NH_3$, and they represented $3H_2$ as 6 connected dots, rather than 3 diatomic pairs. Students do not seem to be able to connect the symbolic expressions used by scientists to the scientific phenomena they are meant to represent. As Krajcik (1991) points out, while students are frequently good at manipulating chemical symbols, they often treat them as mathematical puzzles without possessing a understanding of the chemistry that corresponds to these symbols.

As science of the 21st Century becomes more complex and less available to direct perception and interaction, the challenge will be to help students move beyond their dependence on surface features to develop both their representational skills and their understanding of these increasingly complex scientific phenomena. In doing so, science educators must find new symbol systems and symbolic expressions that allow students to make connections between the things that they can see and manipulate and the underlying invisible science.

BUILDING ON SURFACE FEATURES: MULTIPLE, LINKED REPRESENTATIONS

In general, the relationships between many symbol systems and their fields of reference are arbitrary ones (Goodman, 1979). That is, the specific features of a symbolic element may not have any direct correspondence to those of an entity it represents. For example, there is nothing about the word “cat” that directly corresponds to the species or a particular animal to which it refers. Rather, the word “cat” is a token or symbol that merely stands for a particular animal or the species. The arbitrary relationship between this symbol and its field of reference has been assigned by cultural convention. Its meaning is acquired by use in the context of various cats to which the symbol refers.

The creation of meaning by connecting symbol and referent in the context of use is particularly important for novices to a domain. Because novices rely on surface features and because there is nothing about the features of the word "cat" that correspond to its referent, it would be difficult for someone to assign meaning to this word if it was first encountered outside of the context of a referent. The use of the word in conjunction with a specific referent allows the novice to assign meaning to it based on the surface features of the referent. Once the connection between symbol and referent is established, an image of a cat can be evoked when the word is used, even when a specific referent is not present.

Likewise, acquiring meaning for words and other symbols that scientists use is difficult for novices because the field of reference is frequently not available, often for reasons described at the beginning of this chapter. Words like "expansion of the universe," "evolution of the species," or "molecular reaction" are difficult to understand in large part because students are not able to perceive the phenomena to which they refer. This fact and the dependence of novices on surface features suggest the need for new symbol systems and symbolic expressions that have surface features that more directly and explicitly correspond to scientific entities and processes that are inaccessible because of limitations of time, distance, size, or perception.

Our research and development (Kozma, Russell, Jones, Marx, & Davis, 1996) draws on the assumption that technology can be used to design new symbolic representations with surface features that correspond to and behave like scientific entities and processes. The capabilities of computers play an important role in the design and use of these new representations (Kozma, 1991). The symbolic capabilities of the computer can be used to create graphic elements that correspond to abstract entities that do not otherwise have a concrete, visible character, entities such as “force,” “genotype,” and “molecule.” The computer also has the important capability of being able to “proceduralize” the relationships among these symbols. Arrows, balls, and other symbolic elements can be programmed to behave in ways that are like the “behavior” of forces, genotypes, and other abstract concepts. 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.

Within these software environments, these new symbolic expressions can be linked to other representations that correspond to real world situations or the more formal symbolic expressions used by experts. These referential links between different representations in the software environment can help students make the mental connections necessary to integrate conceptual entities, real world situations, and symbolic expressions used by experts. As a consequence, students can come to have scientifically accurate meanings for the words and other symbols that scientists use that have rather arbitrary relationships to scientific phenomena.

The Design of Representational Environments for Education

Several researchers in this volume (White & Fredericksen; Horwitz; Dede, Salzman, & Loftin; Roschelle, Kaput, & Stroup) have designed computational environments that illustrate these ideas. White, Fredericksen, & Swartz (this volume), for example, designed a series of activities, entitled *ThinkerTools*, in which students operate on symbolic elements to develop a Newtonian understanding of the relationship between force and motion. The activities in this software environment use symbolic elements that stand for real world objects (e.g., space ships or billiard balls, as represented by simple picture graphics), as well as abstract concepts, such as force or acceleration. For example, a symbolic object, such as a space ship, moves across the screen and an additional symbol is used to represent the object's change in velocity over time (i.e., its acceleration). Acceleration is represented by a “dot print” that trails the object and consists of a series of dashed lines the length of which is proportional to its velocity at a given time. As the student uses force (represented by a key press) to act on an object, another symbol called a “datacross” decomposes the force into its *xy* vectorial components. As the learner applies more force (additional key presses) to the object, he or she would see not only the resulting effect on the object as it moves, but a dynamic decomposition of the force into its orthogonal vectors (i.e., the datacross) and a dynamic representation of the change in velocity over time (i.e. its dot print). By interacting with this symbol system, students can acquire an understanding of the relationship between force and acceleration as it is traditionally represented in a force/acceleration equation and as it is acted out in the world. White and Frederiksen demonstrate that this environment is effective in helping even young students understand the complex concepts of force and acceleration.

With ThinkerTools, White and Frederiksen help students understand the relationship between force and acceleration by designing symbolic entities that correspond to these abstractions and then creating links between these symbolic entities that correspond to the underlying science. Links can also be created *across* different representational systems. These cross-representational links can help students extend their understanding to include aspects of the phenomena uniquely represented in the second system, as demonstrated by another environment described in this volume.

Horwitz (this volume) has developed an environment called GenScope that helps beginning biology students understand the relationship between genotype and phenotype, among other pedagogical goals. The genetic model that underlies this environment is represented at five levels: DNA, chromosome, organism, pedigree, and population. At each level, students can symbolically operate on this genetic model and see what happens to a fictional species of dragon. For example, the chromosome level describes phenomena that take place on the scale of a single cell. This level represents the underlying model in two ways, a cellular display in which chromosomes of one specimen of dragon are seen as animated "spaghetti strands," and a diagrammatic display that represents chromosomes with their associated genes in much the same form as they are found in textbook diagrams. Students can combine a cell from a male dragon with one from a female to create a fertilized zygote, which then becomes a new organism. Students can observe the resulting processes of mitosis (cellular reproduction) and meiosis (gamete formation) as QuickTime movies of real cells taken under a microscope running synchronously with computer-generated animations of chromosomes replicating and segregating.

This level of representation is linked with other levels. For example, the student can move up from the chromosome level to the organism level. This allows students to create and observe the organisms that grow out of fertilized zygotes. The model uses information on the genotype of organisms to display their phenotypes, such that the resulting off-spring will have certain observable characteristics (e.g., wings, horns, etc.). As a result of their exploration within these linked representations, students can come to understand the meaning of one symbolic expression in terms of its effect on the second and consequently understand the underlying scientific relationship between genetic processes at the cellular level and physical characteristics at an organism level.

GenScope creates links between representations by making the actions that the student takes within one representation correspond to certain outcomes in another representation. However, 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 number and relative location of symbolic entities could be the same in both representations. In the case of GenScope, chromosomes that appear as "spaghetti strands" in one display at the chromosome level correspond to those in textbook diagrams that appear in the second display at this level. 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. Clearly, several of these linkage mechanisms can be used together in a reinforcing way.

The common information across representations serves several cognitive functions: First, students can use this common information to create identities across representations—that a symbol in one representation means the same thing as a symbol in another representation. Second, the commonality could increase the likelihood that redundant information will be stored in memory. Finally, the common information could provide a cognitively useful means for traversing the multiple representations and integrating information in one representation with that in another. That is, having used the common surface features in two representations to move from one to the other, students then encounter information in the second representation that is in some way "different" from that in the first, as between the cellular and organism levels in *GenScope*. The unique surface features of the second representation express some aspect of the phenomenon in a way that is not or can not be expressed in the first representational system. Students can use this additional information in the second representation to elaborate the understanding formed from the first.

Multiple linked representations in chemistry. We have applied design principles such as these to build a software environment that helps students understand concepts and principles in chemistry (Russell & Kozma, 1994;

Kozma, Russell, Jones, Marx, & Davis, 1996; Russell, Kozma, Jones, Wykoff, Marx, & Davis, 1997). Our goal with this environment is to help chemistry students become more expert-like in their understanding of chemistry and to express their understanding in various ways. The software, entitled MultiMedia and Mental Models in Chemistry, or 4M:Chem, provides the professor in the lecture hall or students in the computer laboratory with a way of exploring chemical systems using multiple, linked representations.

A student might begin a typical session by selecting an experiment, say "Equilibrium," and a chemical system, "N_2O_4/NO_2" for example. The selected system would be displayed as a chemical equation in the "control window" (see Figure 1). The control window allows students to manipulate certain parameters that correspond to the selected experiment (e.g., increase temperature, reduce pressure) and see the effects of their actions as they propagate through simultaneously displayed multiple, dynamic representations that include a video of the reaction, dynamic graphs, displays of instrumental methods used to follow the reaction, and molecular-level animations of the reaction.

For example, the student could select the video window and in the control window change the temperature of the system. The video window would show the system as it appears on the laboratory bench, being heated and changing color as the equilibrium shifts. The students could then select the graph window and "rerun" the reaction. Simultaneous to the video replay, the dynamic graph would show changes in partial pressures which increase or decrease as the system is heated and plateau at equilibrium.

The animation window is designed such that the surface features of the representation correspond to abstract chemical entities and behaviors that students would not otherwise directly observe in the laboratory. In this window, we create symbolic objects that represent the different species of molecules moving and colliding: sometimes reactants form products, sometimes products form reactants.

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. That is, they will come to understand the meaning of each representation in terms of both the surface features of that representation and the surface features of other representations to which it is linked. So for example, based on the surface features of the graph (i.e., the plateau of the lines over time), a student would understand that at equilibrium the partial pressures of the species are constant. The student would take the surface features of the animation (i.e., balls continuing to collide and react) to mean that at equilibrium, reactions continue to occur in both directions. As a result of the link between the two representations—created by the common colors and simultaneous events—students would come to take the plateau of lines to mean *both* that the partial pressures are constant *and* that the reactions continue to occur. The ability to take different representations as meaning the same thing is the skill exhibited by experts (Kozma & Russell, 1997) that we are trying to instill in students.

In our early research (Russell et al., 1997), <u>4M:Chem</u> was used in two sections of general chemistry at a mid-western university. In a pre-post test experiment, students significantly increased their understanding of chemical equilibrium, as measured by tests that asked them to give brief open-ended answers, calculate quantities, and draw diagrams. Also, students significantly reduced misconceptions of the sort identified by Kozma, Russell, Johnston, and Dershimer (1990). In studies reported below, we examine in more detail the cognitive effects of the underlying design principles.

AN EXPERIMENTAL STUDY: THE COGNITIVE EFFECTS OF SURFACE FEATURES

In this study, we tested two principles that underlie our design. The first is that the surface features designed into symbol systems and their symbolic expressions correspond in a direct way to the nature of the understanding that is achieved by using them. A corollary principle is that the use of each symbol system results in a different understanding that corresponds to its unique surface features.

For example, the primary surface feature of the video window is that the color changes when the equilibrium is effected in some way (e.g., the temperature or pressure increases) and the color stops changing when equilibrium is reached. This surface feature would support an understanding that an increase in the temperature or pressure results in a change in the chemical system and that after awhile the system stops changing. The primary surface features in the graph window are the two lines of different colors that increase or decrease over time and then plateau. Students who use the graph window could take these surface features as meaning that the relative amounts of the two species increase or decrease and then stop changing. In the animation window, the continuous interaction of the "balls" or "molecules" represent the dynamic quality of the system such that more reactions lead to products than to reactants but at equilibrium, the relative amounts of reactants and products stay the same and the reactions between reactants and products continue at the same rate.

The second premise that we tested is that the nature of understanding derived from multiple, linked representations is additive, at least to some extent. That is, we expect that students who use videos, graphs, and animations will have an understanding of chemical equilibrium that is a combination of the understanding derived from the individual representations.

To examine the effects of the different representations in our software environment, we enlisted students enrolled in an introductory chemistry course in a community college who were randomly assigned to four different versions of 4M:Chem. Seventeen students completed the study.

Procedure

We configured the software in four different ways so that we could isolate the effects of the different types of representations on student learning. Specifically, three groups of students were assigned to conditions in which they were given the chemical equations for each experiment along with one other dynamic representational form: either the videos (V), the dynamic graphs (G), or the animations (A). A fourth group received video, graphs, and animations.

The content was organized around principles related to chemical equilibrium and addressed common misconceptions that college students have about this concept (Kozma et al., 1990). Students in all groups received a manual that structured their experience with the software. After explaining the instructional purpose of the unit and how the software operated, the manual directed the students through a series of experiments related to the concept of equilibrium, characteristics of the state of chemical equilibrium, and how equilibrium is effected by changes temperature, pressure, and concentration—what is referred to as Le Chatelier's Principle.

Each experiment in the manual used a similar format: predict, observe, explain, conclude. After introducing a particular experiment, the manual asked students a series of questions in which they were to predict the results of a particular experimental manipulation (e.g., increase temperature, increase pressure), make observations of the results of the experiment as displayed in the respective representational form or forms, explain the results (particularly if they disagreed with predictions), and draw conclusions about the nature of chemical equilibrium and the effects of various changes. Students were asked to write their responses to questions in the manual and to think out loud as they progressed through the materials.

Upon altering the system in some way, students would observe the effects of this change as represented by the video, graph, animation, or all three, depending on their assigned group. A voice narration directed the students attention to key features in the representation and described what was occurring. For example, during the heating experiment for the Animation version, the narration said:

> As time passes, notice that the average speed of the red and white molecules increases. Also notice that more red molecules form and only a small fraction of collisions between red molecules produce white molecules.

A group that received the full version of the software (VGA) saw the results of their actions in the following order: First, they saw the chemical equation for the reaction along with a video segment of the experiment, exactly like students in the video (V) condition. Then the experiment was rerun showing a dynamic graph (like the G condition) and following this it was run again showing an animation (like the A condition). Each of these was accompanied by the same narration that students heard in the single representation conditions. After watching the individual representations, students then saw all of the representations together. This was accompanied by a different narration that identified linkages across representations. For example, for the heating experiment, the narration said:

> Notice that as the tube is placed into the hot water bath, it turns a darker brown in the video, while the pressure of NO_2 increases in the graph window, and the number of red molecules increases in the animation window.

In this study, students used the materials individually. There was an experimenter in the room during the session to assist with technical problems, but if students had questions about the chemistry, they were asked to work them out on their own using the software.

Students took a pre-test and a post-test. These tests consisted of items with stimuli and responses that used a variety of representations. For example, students were asked to give definitions, they were given a diagram of a system at equilibrium and asked to draw the diagram as it would represent the system at a new equilibrium, and they were given an animation and asked to draw a graph that represented the animation. It took about two hours for students to complete the instructional materials and both tests.

Results

As a result of their experience with the software, the students as a group significantly increased their test scores from 18.8 % on the pre-test to 50.0% on the post-test (t (16) = 5.49, $p < .05$). Students also significantly decreased the number of misconceptions they displayed when defining chemical equilibrium from a mean of .94 (SD = .66) to a mean of .56 (SD = .51; t (16) = 1.86, $p < .05$). These results correspond to those in previous studies using 4M:Chem (Russell et al., 1997). There were no significant differences between groups on their total scores (F (3, 13) = 1.6, $p > .05$), with the V group scoring a mean percentage of 45.0 (M = 2.5, SD = 2.12), the G group, 58.0% (M = 4.6, SD = 1.52), the A group, 48.0% (M = 3.4, SD = 2.30) and the VGA group, 42.0% (M = 1.6, SD = 2.70).

The first design principle that we tested does not predict higher aggregate scores for one group or another, but it does predict certain qualitative differences in understanding between groups, as measured by items testing different aspects of their understanding. Specifically, the principle predicts that a student's understanding of a phenomenon will be shaped by the characteristics of the unique surface features of a given representation. In this regard, there were important differences between students' understanding who received the Animation, the Graph, and the Video versions that correspond to the respective surface features of these versions, as evidenced by responses to specific test items and questions in the manual.

First, students in the Animation condition (A) did significantly better on three of the ten items dealing with the dynamic nature of equilibrium: the definition of equilibrium, a similar item that asked for the meaning of an equilibrium equation, and an item on the effect of temperature on concentrations of a system at equilibrium. Students in the Animation group had a mean score of 2.4 (SD = 1.34) on these items, while students in the other groups scored .92 (SD =.79, $F(1, 15) = 8.25$, $p < .05$).

The responses of the A group to these three items illustrate the impact of the animation's surface features—the motion and interaction of molecules or "balls" of different colors—on student understanding. What distinguished the students in this group from students in the other conditions was the way they characterized equilibrium in terms of its dynamic properties. For example, in defining the concept of equilibrium, students A17 and A32 said about equilibrium "that reactions still occur but the relative numbers of the substances remain pretty stable (A17)" and that "particles are being formed and separated simultaneously (A32)." Students in other groups more often got this item wrong (e.g., G15: "When the system is balanced between reagent and product."). Or their correct answers did not include comments about the dynamic quality of equilibrium. For example, student VGA13 said, "chemical equilibrium is when the concentration of molecules remains constant over time;" and V23 said, "equal or proportional amounts of reactants and products."

In describing the meaning of a given equilibrium equation, all five of the students in the Animation condition gave correct descriptions after having given incorrect responses on the pre-test. Students A17, A19, and A32 all mentioned the dynamic quality of the system. As A17 put it, "N_2O_4 decomposes to $2NO_2$; $2NO_2$ combines to form N_2O_4." A19 wrote, "Dinitrogen tetroxide goes to react to give 2 mol (sic) NO_2 and vice versa, except there is only one mol (sic) of N_2O_4." And A32 said "N_2O_4 particles will be breaking into 2 NO_2 particles at the same time that the NO_2 particles will be paring to form N_2O_4." Students using other representations more often described the equation merely as an equilibrium reaction. As G24 put it, "Chemical equilibrium between N_2O_4 and 2 NO_2."

This dynamic quality was also exhibited in a question having to do with the effect of temperature on systems at equilibrium. Three of the five Animation students got this correct on the post-test, having given incorrect responses on the pre-test. None of the graph or video students got this post-test item correct and only one of the VGA students got it correct after scoring incorrectly on the pre-test.

Responses to questions in the manual indicates that animation students came to understand the effect of temperature on the energy or "speed" of the molecules and the way this shifts the equilibrium. For example, after using the animations to examine the system at different temperatures, students are asked to predict what will happen to the system when it is cooled. Student A17 said, "Molecules will move slower: N2O4 will dominate. Reactions to NO2 will still occur at equilibrium."

Student A32 responded: "press(ure) down, particles slow movement." This contrasts with students in other groups who did not come to understand the effect of temperature on equilibrium. When asked to predict what would happen when a system was cooled, students in the Video treatment merely said that it would turn a lighter color. Students in the Graph group generally indicated that the pressures of N_2O_4 would increase and NO_2 would decrease. Without a sense of the mechanism or process by which temperature effects equilibrium, students in these groups more often responded incorrectly on the post-test item dealing with the effect of temperature on equilibrium.

A second finding supports the effect of surface features on understanding. Students in the Graph condition (G) did significantly better on two test items that dealt with relative proportions or concentrations of reagents: one item that asked students to construct a diagram that shows the concentration of reagents at a new equilibrium and one asked for the effect changes in pressure on equilibrium. In drawing the diagram, students in the graph condition more often represented all of the species present at equilibrium than did students in other conditions. On the item related to pressure, Graph students more often correctly stated the effect of pressure on a system at equilibrium. Students in the Graph conditions scored an average of 1.4 ($\underline{SD} = .89$) on these two items. Students in the other conditions scored a mean of .33 ($\underline{SD} = .49$; $\underline{F}\ (1, 15) = 10.27$, $\underline{p} < .05$).

In analyzing student responses to questions in the manual, evidence suggests that Graph students used the shape of the curves—particularly the area under the curve and the parallel lines of the graph at equilibrium—to construct an understanding of equilibrium in terms of relative concentrations or “amounts” of the different species which are “constant” at equilibrium. In predicting the effect on equilibrium of increasing the pressure, G11 said “NO_2 will decrease more than N_2O_4,” and G12 said “pressure increase in N_2O_4 then equal amounts of N_2O_4 &

NO_2." When students were asked if the system was in equilibrium at the end of the experiment, G11 said "yes, the two lines are parallel;" while G12, G 16, and G24 all responded positively because the pressures remained "constant."

While the evidence above supports our first hypothesis that surface features of individual representations can shape understanding in particular ways, the results of this study did not support our second hypothesis. This hypothesis states that the use of multiple, linked representatives can have an additive effect over the use of any of the representations individually. As a group, the VGA students did no better than students in the other groups. In fact, only one of the VGA students displayed the multi-representational characteristics that are predicted by the theory. VGA22 scored 10% on the pre-test and 70% on the post-test and eliminated two misconceptions displayed on the pre-test. On the pre-test, VGA22 exhibited common misconceptions by defining equilibrium as "when you have two or more substances which, when mixed, are equal and stop reacting." On the post-test, however, this student correctly responded, that equilibrium is "when the proportion of chemicals in a mixture remains constant."

A look at the responses of this student while using the software shows that he was able to develop his understanding by elaborating knowledge gained in one representation with that gained from others, as predicted by our theory. For example, when asked to predict what would happen to an equilibrium system when heated, VGA22 said, “I think (it would turn) more reddish brown and the molecules will move faster and increase the pressure. The red molecules will become dominant.”

In this protocol, the student displays characteristics from all three of the representations in a linked or coordinated way—the reddish brown color represented in the video, the motion of the molecules represented in the animation and the increase in pressure represented in the graph.

Unfortunately, this student was the exception rather than the rule for the VGA treatment. Two of the other VGA students persisted in their misconceptions on the post-test with VGA18 saying that “chemical equilibrium is a state in which a chemical reaction stops occurring.” VGA20 says it is “when all the chemicals are equal.”

Several questions asked students to report their observations as they conducted their experiments. The responses to these questions show the ways VGA students processed the representations. Responses to these questions show that color was the most salient feature used by these students. When asked to describe what happened when students increased the temperature on the system, four of the VGA students reported only that “the color darkened.” When conducting the pressure experiment, students were asked to describe the characteristics of a system when it reached equilibrium. Again, color dominated the responses of VGA students: VGA13 said, "The color would not change." VGA18 said "It would be darker." VGA20 said, "Color would be less." And VGA27 said "lighter color."

Discussion

As a group, the students significantly increased their understanding of equilibrium and reduced their misconceptions when they used *4M:Chem*. The results of this study and those in other chapters in this volume (White & Fredericksen; Horwitz; Dede, Salzman, & Loftin; Roschelle, Kaput, & Stroup) demonstrate the potential that technology has for providing designers with a powerful new symbolic pallet which can be used to create effective instructional environments. The graphic and computation capabilities of computers can be used to design new symbol systems and symbolic representations with surface features that correspond to and behave like the abstract scientific entities and processes in the mental models of experts. These environments can provide students with access to complex scientific concepts that are otherwise inaccessible because of limitations of time, distance, size, or perception.

At the same time, the findings of this study highlight the potential limitations of these environments. The effectiveness of these environments depends heavily on the cognitive strategies that students use in response to the strategies used by designers. In 4M:Chem, symbolic elements in the various representations were referentially linked so as to help students make the mental connections from one representation to another that would allow them to integrate their understanding across representations. The hypothesized mechanism for the additive effect of these multiple representations is a two-step process. First, students would use the linkages, or common surface features, to establish identities between representations and thus move from one representation to another. Having done this, the students could then use the unique surface features of the second representation to elaborate or add onto an understanding gained from the first. For example, one would expect the VGA group to have displayed both an understanding of the dynamic character of equilibrium gained from the animation and the relative concentration of reagents gained from the graph. However, contrary to this prediction, the VGA group did not make the predicted elaborations and they did not do as well as the animation group or the graph group on these items.

Evidence suggests that students did engage in the first step of the hypothesized two-step process; they made links across representations. Color and simultaneity of events were the primary surface features used to create linkages across representations in 4M:Chem. For example, the reddish-brown color that appears when equilibrium shifts to NO_2 in the vessel in the video is also the color used in the graph to show the increased concentration of NO_2 and the color of the NO_2 molecules in the animation. That these common features were successful in helping students make a connection among the representations is attested to by the fact that students in the VGA group frequently referenced color and a change of color in response to a wide range of questions regarding equilibrium.

However, students in the VGA group did not engage the second step of the process; they did not elaborate on their understanding of equilibrium beyond a change in color. Rather than building on their connection among representations and using the combination of surface features to elaborate their understanding, evidence suggests that color became the subset of surface features that students attended to most (i.e.,a kind of "least common denominator"). The students in this group did not acquire the meanings for the unique features of the individual representations, such as the continuos reaction of products and reactants and the proportional changes in reagents. Since there are aspects of equilibrium that color change by itself can not explain, students in the VGA group did no better than students in other groups on the post-test.

As a result of this study, we were left to figure out how we could tune the design of the environment to help students use the connections that they were making across representations to think more deeply about equilibrium and extend their understanding. We wanted students to be able to identify the unique features of the different representations and consider their meaning as they relate to the meaning of other representations.

BUILDING ON SOCIAL DISCOURSE

Pea (1992, 1993) and others (Newman, Griffin, & Cole, 1989; Brown, Collins, & Duguid, 1989) consider meaning to be the product not just of individual cognition but also of social interaction. From this viewpoint, social interaction is not a one-way transmission and reception of meaning, but a two-way transformative process by which meaning emerges in the space between two interlocutors.

In this space, meaning is socially constructed through processes of negotiation and appropriation by two people engaged in joint activity. That is, meaning is negotiated 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. In the course of discussion, one party may appropriate, or express the meaning taken from another. In a reciprocal manner, the second party may come to mean more than originally thought as a reply is composed to affirm, disconfirm, or elaborate on the interpretation of the other. Through this discourse, interlocutors may converge on shared meaning that is more than either understood in the beginning. More important, they come to engage in a process of achieving expertise. From this perspective (Pea, 1992; 1993), expertise is defined dynamically as a continuing process of participation in a discourse community, rather than merely as a particular a set of problem solving skills and conceptual structures that one might have at the moment. This definition is supported by the kinds of interactions found by Amman and Knorr-Cetina (1990) in their study of scientists in a genetics laboratory and by our ethnographic study in chemistry laboratories (Kozma, Chin, Russell, & Marx, 1997).

However, as Coleman (1995) points out, research on argumentation and conversational analysis in schools has found that the discourse strategies students normally use while engaged in collaborative science rarely result in the extended inquiry or shared meaning that is envisioned above. Rather than refine understanding collaboratively through extended discourse, students make and defend vacuous claims and rarely produce explanations or justifications for their answers. They tend to routinely criticize or dismiss each other's ideas and, quite often, the consensus that emerges rests on the status of individuals rather than on the nature of student discourse.

Taken together, the implication drawn from these researchers is that designers should provide students with environments that restructure the discourse in science classrooms around collaborative knowledge building and the social construction of meaning (Coleman, 1995). The intent of this restructuring is to have students actively engage in a questioning and explanation process in which they evaluate each others' queries and assertions in the effort to collaboratively revise their own theories and beliefs about the phenomena in the world that they are trying to understand.

Technology can play a significant role in structuring and augmenting these learning conversations (Pea, 1992; 1993). First, technological environments can be designed to provide students with symbolic elements that enable students to establish common attention to referents or coreference within their discourse; these symbols give them something specific to talk about. Second, activities in these environments can engage students in focused inquiry that involves authentic scientific tasks, such as making predictions, observations, and explanations that support their sense making conversations.

We felt that the intersection of these two features could yield the most compelling strategies for our chemistry software environment. By providing students with inquiry activities *and* with symbolic representations that have surface features that correspond to and behave like abstract scientific entities and processes, we can support conversations in which students use surface features to act on and make predictions, observations, and explanations about scientific phenomena that are otherwise unavailable to them. The combination of symbolic representations and inquiry activities enables and constrains the range of meanings generated by discourse, such that students can build on each other's ideas and intentions, draw new ideas into a common frame of meaning, and repair discrepancies (Roschelle, 1992). Our prediction is that student engagement in such conversations while using 4M:Chem will result in sustained inquiry and a more extended consideration of what the features of representations mean, as they relate to those of other representations. Ultimately, students will come to have a better understanding of the underlying science.

A PILOT STUDY: STUDENTS USING MULTIPLE REPRESENTATIONS TOGETHER

We made several changes in our software that would structure and augment the conversations of student pairs, as they collaborate on joint investigations. First, we removed the audio narrations from the software, since we felt these would compete with and reduce student conversations during their use of the environment. In our use of *4M:*Chem, we give only one manual to the two students in a pair and asked them to come to some agreement, if possible, in recording their answer. If students disagree, they are instructed to try and convince each other of their position, using whatever evidence was available. We added questions to the manual that ask students to explicitly identify the function of certain surface features of each of the representations. For example, in the heating experiment, students are asked:

> What property of the graph allows you to judge whether the amounts of N_2O_4 and NO_2 in the sample at the right are changing over time?

All of these changes were made to engage students in extended discussions and in joint consideration of the meaning of symbolic elements and symbolic expressions.

In a pilot study, we conducted a detailed analysis of the use of this version by two male university students (AR and MN) enrolled in an introductory chemistry course. During their use of the software, the students had access to all four representations, much as in the VGA condition of the experimental study. These students were guided through the experiments by the revised manual, described above. As in the earlier study, students were asked to predict, observe, explain, conclude, and enter their responses in the manual.

We audio and video taped the students during their session and the session was transcribed. The videotape was observed by researchers and the session was coded by the type of physical references students made to each representation.

Each coded reference was associated with the corresponding verbal statement in the transcript. The transcript was then analyzed to identify ways that the software enabled and constrained the social construction of meaning.

Both of the students in our pilot study began the session with significant misconceptions about chemical systems at equilibrium. AR defined equilibrium as when "the chemical reaction has taken place and at this point there is no further change." MN defined it as "the point at which a chemical reaction does not move either way." At the end of the session, AR defined equilibrium as "The point [at which] the reactions have stabilized and the changes are constant." MN 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.

The two students interacted with each other and the system for an hour and twenty-three minutes. During this time they took 307 conversational turns. They also made 115 physical references to the screen: 26 to the video, 39 to the graph window, 28 to the animation window, and 22 to the equation in the control window. The references included 91 points to a specific feature with fingers or the mouse cursor, 12 traces of the shape of a specific feature (typically following the line of a graph), and 12 waves of a more general reference. These references were fairly evenly divided between the two students, with 60 made by one student (MN) and 55 made by the other (AR).

In the following sections, we analyze the students' discourse as they engage in activities and interact with specific features of the various representations. In our analysis, we looked for specific instances where students came to understand equilibrium as continuous, dynamic reactions among all species in the system. We looked for the discourse moves that resulted in this understanding and for ways these moves were supported by the students use of surface features within and across representations.

Using Surface Features to Co-Construct Understanding

The students began their investigation by observing the NO_2/N_2O_4 system as it achieves equilibrium from two different starting states: one in which the system starts warm and then cools down to room temperature, and one in which the system starts cool and then warms up to room temperature. The manual directs the students to observe these phenomena using different representations—video, graphs, and animations—singularly and together, in conjunction with the equation that appears in the control window. The manual asks them to make inferences about the system at equilibrium, based on certain features or properties of the representations.

For example, after having viewed the system in the video window, the manual asks, *What observable property would allow you to judge the relative amounts of* N_2O_4 *and* NO_2*in these two samples at the beginning of the experiment?* (In the protocol sample below, italics will be used as indicating that the manual is being read.) In response to this question, the students write: Color. N_2O_4 is yellow at -8° C, with addition of heat turns orange (NO_2). (In the protocol, underlining will indicate that a portion of the discourse is being written in the manual.)

While viewing the representations and discussing the observations and responses to the manual, students made verbal and physical references to specific features of representations. For example, at one point while viewing the graph of the cooling experiment (see Figure 2), AR says: "Equilibrium? Like equilibrium is right there, or something?" **[Points to the intersection of the lines in the graph.]** (Pointing, gestures, and other physical actions are indicated by bracketed bold words, in the protocol below.) Through his pointing, AR 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).

However, as a result of their interaction, AR and MR 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 software. At the point where we pick up the conversation, the students have run the cooling experiment with the video window, the graph window, and the control window open (see Figure 2). The students are responding to the question in the manual that reads: *Describe what you observe in the graph window*.

1. **MN**: The concentrations crossed at equilibrium. Actually, is that crossing at equilibrium. Or is it just . . .

2. **AR**: Reaching it.

3. **MN**: 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.

4. **AR**: 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.

5. **MN**: So, what does that say about equilibrium?

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

7. **MN**: **[MN reruns the cooling experiment, as it appears in Figure 2.]** 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 vial of NO_2 in the video.]**

8. **MN**: 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.

9. **AR**: So, it should be darker?

10. **MN**: So, is this equilibrium right here then? **[MN traces the plateau of the NO_2 line in the graph.]** Or is this? **[He points to the intersection of the lines.]**

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

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

13. AR: So maybe it's at five minutes and not where they cross?

14. MN: All right.

15. AR: "*Describe what you observe in a concentration graph.*" Um, garph [sic].

16. AR: Graph. Um-

17. MN: Let's see. Um the pressures are just equalizing to their equilibrium for each gas.

18. AR: Actually, they're oscillating. <u>Pressures oscillate</u> (**MN**: Are they oscillating?) to equilibrium when the pressure is unchanging or the pressure is not changing much.

19. MN: Okay. "*What property of the graph allows you to judge whether the amounts of N_2O_4 and NO_2 in the sample on the right are changing over time?*" Well, obviously if the slope is bigger than zero.

20. AR: "*What property of the graph allows you to judge whether the amounts-*"

21. MN: See, since the- I'm gonna do this again. **[MN reruns the cooling experiment.]** When they're- obviously, when it has a slope **[MN sticks his hand out at a slant, fingers together.]** it's going to be changing. When it levels off **[He holds his hand parallel to the ground.]**, there's no change. Make sense? All right.

22. AR: <u>Level. No change</u>.

23. MN: All right. Well, that answers our question then. It's not when they cross. All right.

24. MN: "*Using this property, how can you tell when the sample is at equilibrium and when it's not?*"

25. AR: When a sample-

26. MN: <u>Whenever the line is- has a slope of zero.</u>

27. AR: When- yeah.

28. MN: Okay.

This brief segment of discourse shows a significant transformation in the meaning that MN and AR 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. This misunderstanding is compounded by a misinterpretation of the graph of equilibrium, exhibited by MN in Line 1 and AR in Line 4. The students take a particular surface feature of the graph to mean that the partial pressures are equal (an accurate interpretation) and that at this point the system reaches equilibrium (a scientifically inaccurate interpretation). In Line 3, MN 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 (Lines 25-28), the students come to take plateau to mean equilibrium, rather than the crossing point.

How does this transformation come about? First of all in Line 3, MN 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? By expressing his confusion to AR in Line 1, it becomes part of their joint activity and AR 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. In Line 7, MN 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 AR in Line 10 and ask again for an interpretation of the graph. AR resolves the issue in Line 11 by pointing to the plateau of the lines. Even though MN is the person that raised the problem and notices the feature in the video that leads to the resolution of the issue, AR—the person who was satisfied with the original interpretation—serves the important function of confirming the resolution by changing his interpretation (Line 13). The students cycle through this resolution again in Lines 21 through 23, as MN links his interpretation of the graph to yet another representation, one that he generates himself, the slope and plateau formed by his hand. By Lines 25 through 28, the students have completed their negotiation of the new interpretation of the graph: the system is at equilibrium when the slopes of the lines are zero.

However, the students have not yet come to the understanding that at equilibrium the reactions continue to occur. At this point in the session, they are still focusing on the understanding of equilibrium as "unchanging." This understanding of equilibrium is now consonant with their interpretation of the graph. Given this alignment and the surface features that are available, there is nothing at this point that supports their further transformation to an understanding of equilibrium as dynamic and continuous. This change in the students' understanding does not occur until the students begin to use the animation.

At the point where we pick up with the following protocol, the students have rerun the heating experiment with all four windows open. The statement in the manual that they are considering is, *Describe what you observe in the animation window over time*.

29. AR: *"Describe . . . animation over time."* Which color is it?

30. MN: Okay. N2O4. **[MN points to the N_2O_4 line on the graph.]** Those are the double molecules. **[He points to an N_2O_4 molecule.]**

31. AR: What happens over time? There's more N_2O_4 than NO_2 over time. There is . . .

32. MN: Less.

33. AR: Oh, I didn't see you start. Okay. There's less N_2O_4 and more NO_2?

34. MN: Mm hm.

35. AR: Okay.

36. AR: *"Describe what you observe in the animation window when the sample on the right reaches equilibrium at room temperature."* Which would be pretty soon.

37. MN: Yep.

38. AR: All right.

39. MN: It's probably gonna be . . . it's probably not gonna change any more. That's all. The molecules are gonna keep transferring back. I mean, they're still gonna be . . .

40. AR: They're gonna go back and forth but by the same amount.

41. MN: At the same rate.

42. AR: <u>Molecules still change but they're amount stays close to the same</u>.

43. MN: Okay.

By the end of this segment, both MN and AR have come to have a deeper, more scientific understanding of the unchanging yet dynamic quality of equilibrium. This understanding is supported by the dynamic surface features of the animation that show molecules moving around, colliding, and reacting to form both products and reactants. This representation is physically connected to the graph when MN points to the line for N_2O_4 and to its corresponding surface feature in the animation (Line 30). In Lines 36 through 38, the students agree on a particular point in time during the animation ("Which would be pretty soon," AR, Line 36) as being when the system is in equilibrium. They then use the surface features of this representation to extend their understanding of equilibrium, previously negotiated around the graph.

How does this extension occur? It starts with the notion of equilibrium as not changing. The "not going to change anymore" expressed by MN in Line 39 gets appropriated and reinterpreted by AR in Line 40. He then uses the surface features from the animation to interpret not changing as going "back and forth but by the same amount." In Line 41, MN reciprocates by extending the interpretation to mean at "the same rate." At this point, "unchanging" has come to mean "same amount" and "same rate" and this allows for their scientifically accurate, shared understanding of the unchanging nature of equilibrium to include the dynamic, changing notion of molecules that keep transferring (MN, Line 39) back and forth (AR, Line 40).

The results of this pilot study support the prediction that the use of a modified version of <u>4M:Chem</u> in a social context will result in sustained inquiry and an extended consideration of the meaning of the surface features of multiple linked representations. Of course, these findings would need to be reproduced in future studies. Still, the students in this study were able to go beyond the surface features of the representations to develop a deep, scientifically accurate understanding of the dynamic, molecular aspects of chemical equilibrium that are not otherwise directly perceivable. These surface features supported the students' processes of appropriation, negotiation, and convergence toward their shared understanding. While engaged in these processes, the students replicated the discourse practices seen in studies of scientists interpreting the meaning of representations in their laboratories (Amman & Knorr-Cetina, 1990; Kozma, Chin, Russell, & Marx, 1997).

CONCLUSIONS

This chapter began by describing how important signs and symbols are to scientists and to the understanding of scientific phenomena, particularly complex phenomena that are not directly perceivable. Scientists are very skilled in using different symbol systems and symbolic expressions in a flexible way to represent these scientific phenomena and solve problems related to them. This is sometimes an effortful activity that engages scientists in deliberation and argumentation and involves the use of representations in the making of claims and warrants. Novices are less skilled in the use of representations and rely on their surface features for meaning. Quite often, the surface features of physical phenomena and symbol systems do not correspond to the complex, underlying scientific entities and processes. Furthermore, students are unable to engage in extended inquiry and have difficulty in constructing shared meaning.

In this chapter, we examine the use of software environments to provide students with new representations that have surface features that correspond to and behave like underlying scientific entities and processes. In our experimental study, the unique surface features of different representations shaped the students understanding of equilibrium in characteristic ways and students used the surface features shared by multiple representations to make connections across them. However, students were not able to use these connections to elaborate their understanding of the underlying scientific phenomenon. In a pilot study, we then showed how students using the system in pairs can engage 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 equilibrium and replicated the discourse practices of scientists.

The results of this research demonstrate the potential that technology has for providing designers with a powerful new symbolic pallet that can be used to support student thinking and augment student discourse. However, these new symbol systems by themselves are often insufficient to aid learning. The results of our pilot study suggest that these new symbol systems and their symbolic expressions may best be used within rich social contexts that prompt students to interact with each other and with multiple symbol systems to create meaning for scientific phenomena. These results also argue for continued research on the impact of symbolic environments on the cognitive processes and social practices of science learning.

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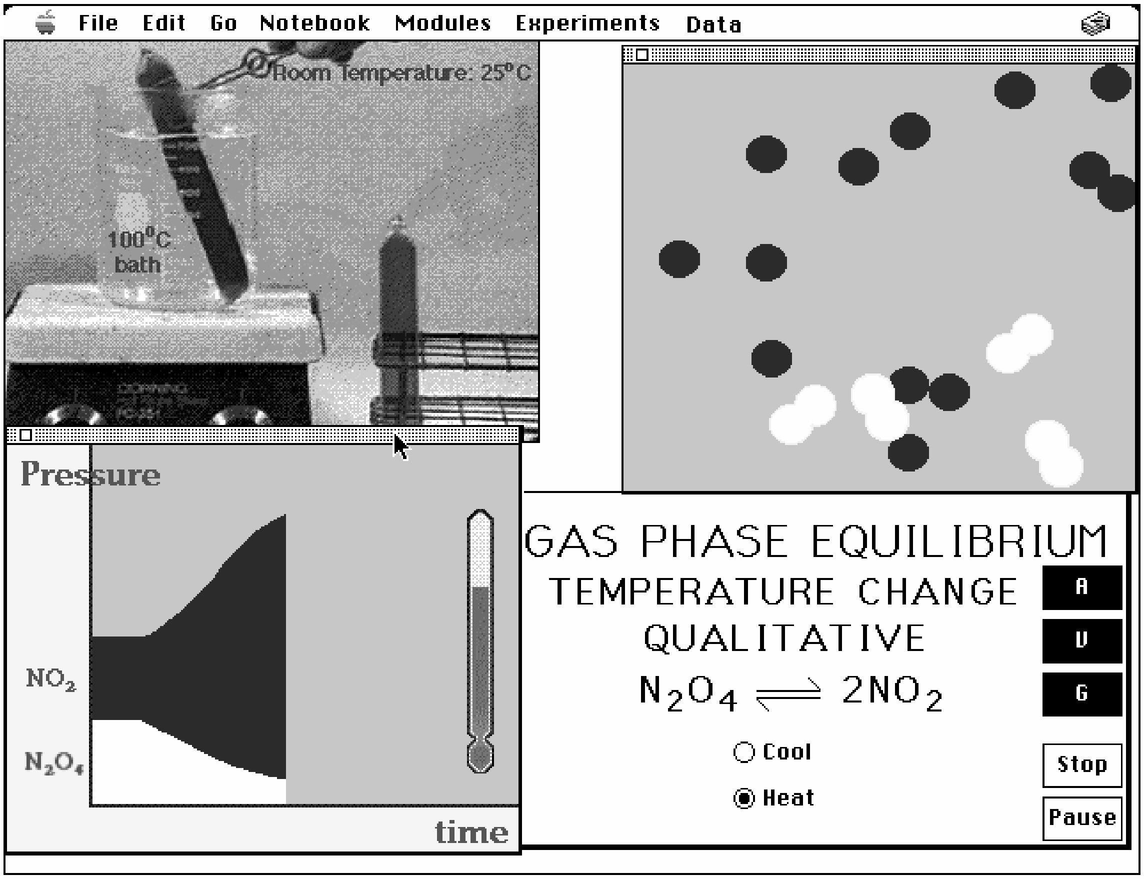

Figure 1. Sample screen from *4M:Chem* showing Video, Animation, Graph, and Control Windows open. Original in color.

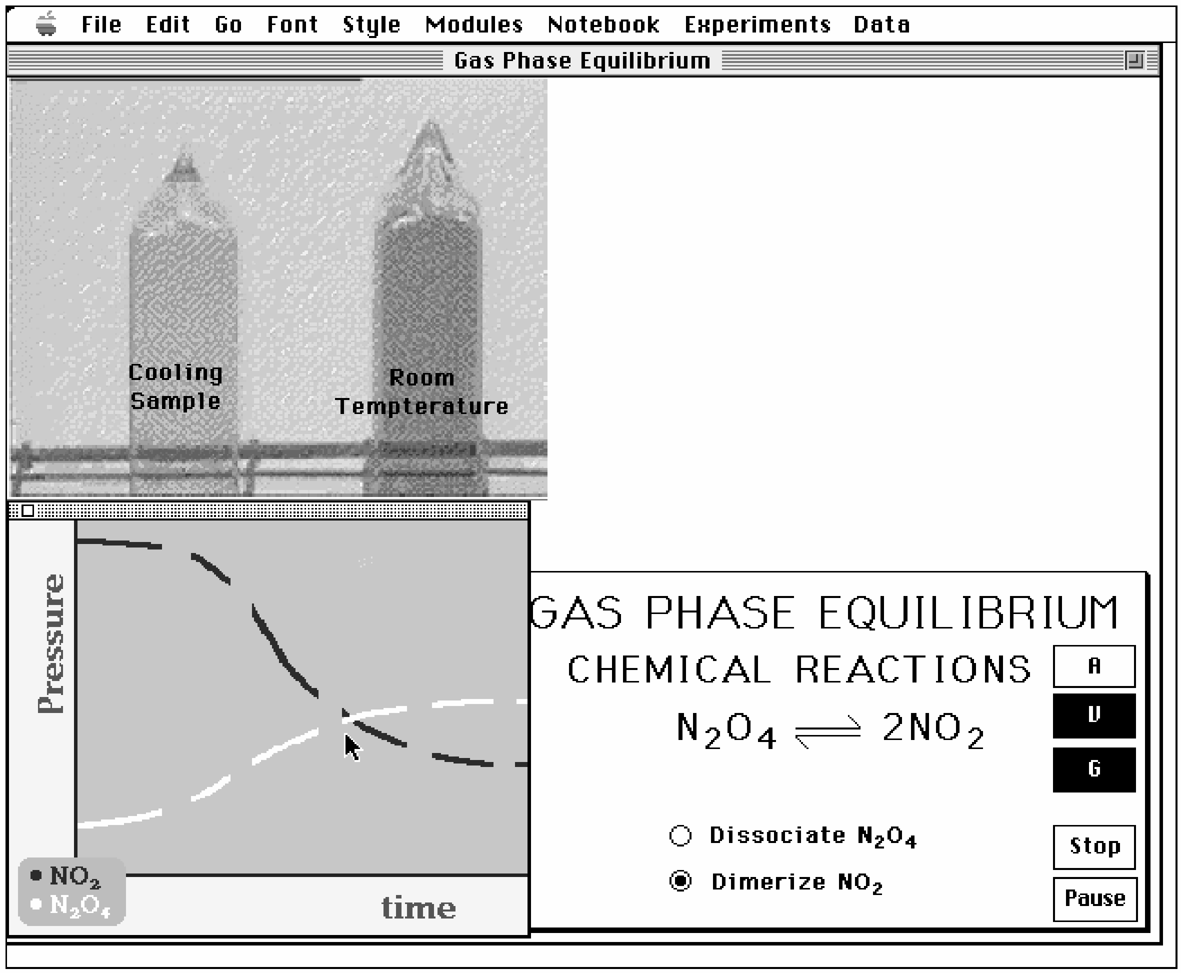

Figure 2. State of the screen at the time MN and AR are discussing the graph at equilibrium (Lines 7-18 in the protocol).