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Multimedia Learning of Chemistry

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Abstract

This chapter proposes the use of a "situative" theory to complement the cognitive theory of multimedia learning of chemistry. The chapter applies situative theory to examine the practices of chemists and to derive implications for the use of various kinds of representations in chemistry education. The two theories have implications for different but complementary educational goals—cognitive theory focusing on the learning of scientific concepts and situative theory on learning science as an investigative process. We go on to present and contrast several examples of multimedia in chemistry that address each goal. We critically review the current state of research on multimedia in chemistry and derive implications for theory development, instructional design and classroom practice, and future research in the area.

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What is the Multimedia Learning of Chemistry?

Multimedia to support cognition. Richard Mayer (this volume; 2003; 2002, 2001), and others (Schnotz, this volume; Sweller, this volume) describe an information processing, cognitive theory of learning. There are three tenets at the base of this theory: dual channel input, limited memory capacity, and active processing. Mayer draws on this theory to develop a series of design principles for multimedia presentations that use both auditory-verbal and visual-pictorial channels, address limited cognitive capacity for storing and processing information from these channels, and support students' active selection, organization, and integration of information from both auditory and visual inputs. These authors present compelling research in support of the finding that the implementation of these principles results in deeper learning—that is, understanding of difficult concepts and principles which can then be used to solve novel problems. Among the principles most relevant to chemistry learning are the:

- Multimedia Principle: Learning from words and pictures results in deeper learning than learning from words alone.
- Contiguity Principle: People learn more deeply when corresponding words and pictures are presented near rather than far from one another in space or time.
- Modality Principle: People learn more deeply from animation and narration rather than animation and on-screen text.
- Signaling Principle: People learn more deeply when guidance is provided for directing the learner's attention.
- Interactivity Principle: People learn more deeply when they can control the order and pace of presentation.

The application of these principles to instructional presentations could make important contributions to the learning of students who have significant difficulties understanding key chemistry concepts and principles (Gable, 1998; Gable & Bunce, 1994; Nakhleh, 1992). For example, the Multimedia and Modality Principles would suggest that designers of multimedia chemistry software that illustrates a difficult concept, such as equilibrium, provide narrated molecular animations in which chemical species are presented in different colors and the concentrations of these species shift over time until the point of equilibrium is reacted. The Signaling Principle suggests that narration of the animation could point out the concentrations of each species are changing; it could identify the point at which the system has reached equilibrium; and it could mention that at equilibrium, the forward and backward reactions continue at the same rate. The Interactivity Principle could allow the students to manipulate temperature or pressure and look at the impact this has on the equilibrium of the system. Indeed, we found that such software results in increased student understanding of this difficult concept (Kozma, Russell, Jones, Marx, & Davis, 1996), as described in detail in the following section.

<u>Multimedia to support practice</u>. However, in the field of chemistry as well as other sciences, various external representations such as diagrams, equations, formulae, and graphs serve a more profound role in the understanding and practice of scientists than that implied by the use of pictures, diagrams, or animations in multimedia instructional presentations. The daily practice of chemists depends heavily on the use of various representations to shape and understand the products of chemical investigations. For example, in our study of professional chemists in an academic and a pharmaceutical

chemistry laboratory (Kozma, Chin, Russell, & Marx, 2000), we found that chemists used multiple representations together to construct an understanding of the chemical phenomena they investigated in their experiments. Chemists used structural diagrams to describe the composition and geometry of the compounds that they were trying to synthesize. They used diagrams and chemical equations to reason about the reaction mechanisms needed to transform reagents into products and the physical processes that would support these transformations. Chemists analyzed various instrumental displays and printouts to verify the composition and structure of the compounds that they were trying to synthesize. As they worked together to understand the results of their investigations, chemists made references to specific features of the printouts (e.g., peaks on NMR or mass spectra) as warrants for claims that the desired products were obtained.

The ways these representations are used by chemists has important implications for the use of multimedia in chemical education, if the educational goal is to develop students' practice of chemistry as an investigative scientific process. National science standards emphasize the learning of science as both a body of significant concepts and as a process of investigation. For example, the National Science Education Standards (National Research Council, 1996) state that this new vision of science standards "requires that students combine processes and scientific knowledge as they use scientific reasoning and critical thinking to develop their understanding of science. . . Science as inquiry is basic to science education and a controlling principle in the ultimate organization and selection of students' activities" (p. 103). These complementary goals are both addressed in this chapter.

However, the goal of learning as a process of ongoing investigation requires a different theoretical base; one focused on knowledge as practice, as well as on the acquisition of concepts and principles. Greeno (1998), Roth (1998, 2001; Roth & McGinn, 1998), and others (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991) describe a *situative theory* of learning and understanding in which the practices of a community are influenced by the physical and social characteristics of a specific setting and, in turn, the characteristics of the setting are influenced by the community of practice. In these settings, characteristics of physical objects and social resources enable or constrain the way people can talk, think, understand, etc. For example, discussions about the color, viscosity, smell, etc. of solutions are enabled by the physical characteristics of chemical reagents in the laboratory. Beyond physical objects, *representations* play a particularly important role within situative theory because the use of representations enables the consideration and discussion of objects and processes that are not present or otherwise apparent in a specific situation, as it did for the chemists in our observational study who used representations to discuss the molecular structure of their reagents (Kozma, Chin, Russell, & Marx, 2000). Through the use of structural diagrams, equations, and instrumental printouts chemists are able to visualize, discuss, and understand the molecules and chemical processes that account for the more perceivable substances and phenomena they observe in the laboratory.

Greeno (1998) characterizes classrooms that are oriented toward situative theory as ones that encourage students to participate in activities that include the formulation and evaluation of conjectures, examples, applications, hypotheses, evidence, conclusions, and arguments. Conceptual understanding occurs in the context of these participatory activities. In these participation-oriented classrooms, discussions are organized not only to foster students' learning of subject-matter concepts and principles, but also their learning to participate in authentic practices—in the case of chemistry, scientific investigation. From this perspective, multiple representations are used by students not only to express their understanding of key concepts in the domain, but also support students’ engagement in authentic science practices, such as asking research questions, designing investigations and planning experiments, constructing apparatus and carrying out procedures, analyzing data and drawing conclusions, and presenting findings (Krajcik, et al., 1998).

The use of representations to support chemistry practice is illustrated by an observational study one of us conducted in a university organic chemistry course in which we examined pairs of students as they interacted with each other while synthesizing a compound in the wet lab (Kozma, 2000a). We observed that unlike chemists, chemistry students in this study rarely used representations in the laboratory and, as a consequence, their practices and discussions were focused exclusively on the physical aspects of their experiments. The primary interaction among student lab partners was focused on setting up equipment, trouble shooting procedural problems, and interacting with the physical properties of the reagents they were using (e.g., was their crystalline product washed enough or dry enough?). We observed very little discussion among students about the molecular properties of the compounds they were synthesizing or the reaction mechanism that might be taking place during their experiments. However in a subsequent session, these same students worked together while using a *molecular modeling* software program that allowed them to build, examine, and manipulate representations of the same compound that they synthesized in the previous wet lab session. During the computer laboratory session, student discourse—much like the discourse we observed among professional chemists (Kozma, et al., 2000)—was filled with references to the molecular properties and processes that underlie the chemical synthesis that they previously performed in the wet lab.

A number of principles for the design of learning experiences and multimedia resources can be derived from situative theory (Kozma, et al., 2000). For example, teachers could engage students in the generation of visualizations as a way to pose their research questions, make predictions, or state the goals of their investigations. When designing their investigations, students could be prompted to think about the representational form of the data they will collect, how it would be displayed, and why a particular display might work better for their purposes than another. When constructing their apparatus, they could describe the relationship between the physical changes they expect to observe and the data that are generated by instruments. The representations generated by these instruments could 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 chemistry. In presenting their findings, students could use these displays along with other representations to explain their findings and argue for their conclusions. In this regard, it could be particularly effective to use the features of multiple representations together (such as student-generated structural diagrams and instrument-generated printouts) to explain the results and serve as the warrants for conclusions about findings. Indeed, we found that students increased their use of representations in this way when provided with representational environment to support their laboratory investigations, as detailed in the next section.

In the remainder of this chapter, we extend our consideration of both cognitive and situative theories to examine their relevance to multimedia learning of chemistry. We examine and contrast applications of these theories to two examples of multimedia chemistry environments developed in our laboratories, as well as those developed elsewhere in the United States. We consider the results and the limitations of research on multimedia in chemistry, along with their implications for learning theory, instructional design and classroom practice, and further research needed in this area.

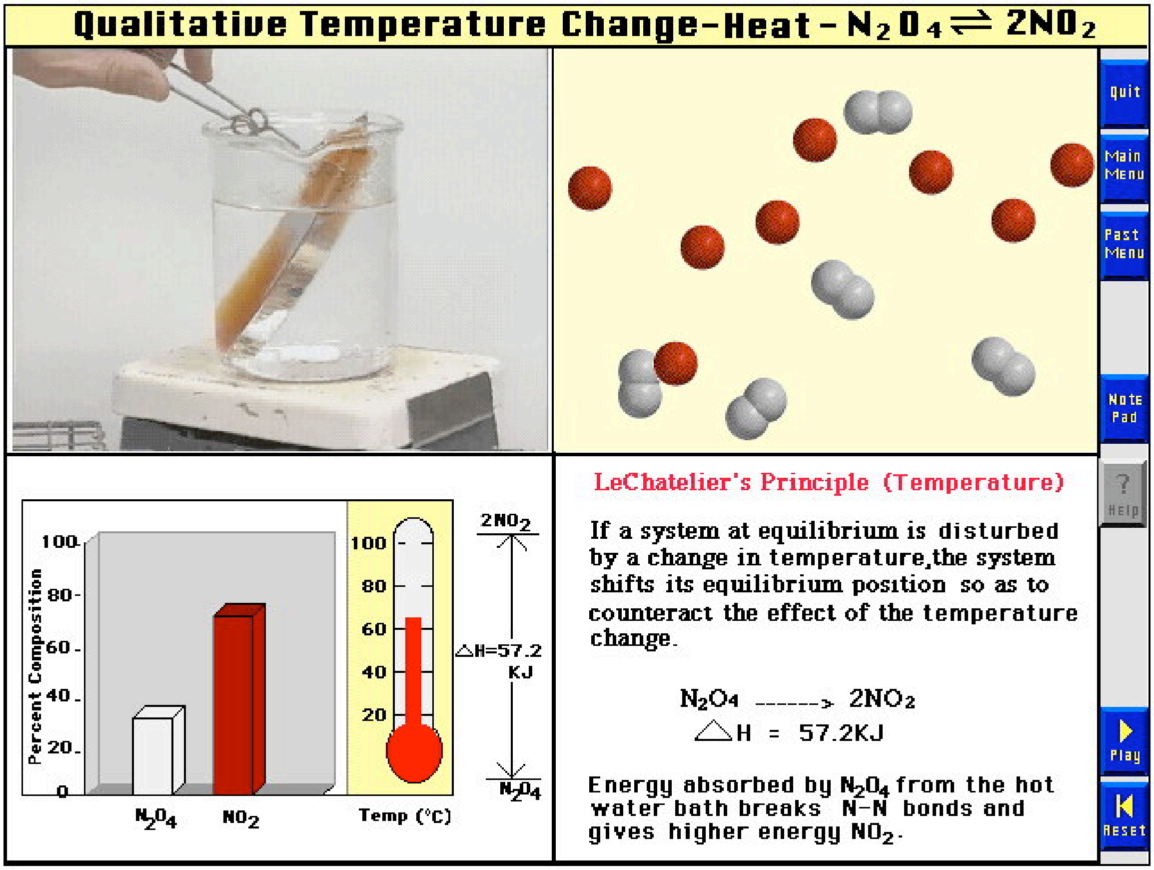
Examples of Multimedia Learning of Chemistry

Multimedia to support the learning of concepts and principles. Several examples of multimedia learning of chemistry illustrate the contrasting and complementary nature of the cognitive and situative perspective. Our first example, *SMV:Chem* (*Simultaneous Multiple Representations in Chemistry*) and its prototype predecessor, *4M:Chem* (*MultiMedia and Mental Models in Chemistry*), illustrates the application of cognitive theory. *SMV:Chem* (Russell, Kozma, Becker, & Susskind, 2000) is a multimedia chemical software program designed to show experiments illustrating key chemistry concepts using molecular-scale animations, graphs, molecular models, and equations. *4M:Chem* (Russell & Kozma, 1994; see also Kozma, et al., 1996; Russell, Kozma, Jones, Wykoff, Marx, & Davis, 1997) was a prototype used to develop the technology and test some of the underlying theoretical principals. These packages were designed for use both by the instructor in the classroom during lecture and by students outside the classroom as part of homework exercises. Both programs used a screen design that displayed videos of experiments in the upper left quadrant, *nanoscale* animations in the upper right quadrant, graphic representations in the lower left, and other representations such as chemical equations, text, data collection sheets, and molecular models in the lower right quadrant (see Figure 1).

The screens in Figure 1 show on the right tool bar the navigation controls for a specific experiment. Each of these four windows can be independently activated such that users can view a single window or any combination of windows. There is an audio track for the video window describing the experiment. There are separate audio tracks for the other three windows that can be activated when a window is viewed by itself.

Figure 1 illustrates LeChatelier's principle for a gas phase equilibrium, $N_2O_4(g)$ _ 2 $NO_2(g)$, subject to a change in volume. The concept of equilibrium is very difficult to understand, as documented by numerous studies of student misconceptions of this topic (Banerjee, 1995; Camacho & Good, 1989; Gorodetsky & Gussarsky, 1986; Kozma, Russell, Johnston, & Dershimer, 1990; Thomas & Schwenz, 1998).

As the experiment proceeds, the video window shows a change in equilibrium composition that produces more N_2O_4 resulting from increasing the temperature (Figure 1). The experiment starts with two tubes containing equilibrium mixtures of these two gases. One tube is placed in a boiling water bath. Students are able to observe that after this change in temperature the color of the gas in the heated tube is darker than the color of the gas in the room temperature tube because the composition has shifted to produce more red-brown NO_2 (a monomer) leaving less colorless N_2O_4 (a dimer). The animation window shows initially equal numbers of red-brown spheres and coupled gray spheres all in constant motion. Prior to increasing the temperature, the distribution of species is seen to fluctuate with at times two more red-brown monomers and one less gray dimer as the dimers decompose and the monomers dimerize showing the dynamic property of a chemical equilibrium.


Qualitative Temperature Change-Heat - $N_2O_4 \rightleftharpoons 2NO_2$

LeChatelier's Principle (Temperature)

If a system at equilibrium is disturbed by a change in temperature,the system shifts its equilibrium position so as to counteract the effect of the temperature change.

N_2O_4 ------> $2NO_2$

$\triangle H$ = 57.2KJ

Energy absorbed by N_2O_4 from the hot water bath breaks N-N bonds and gives higher energy NO_2.

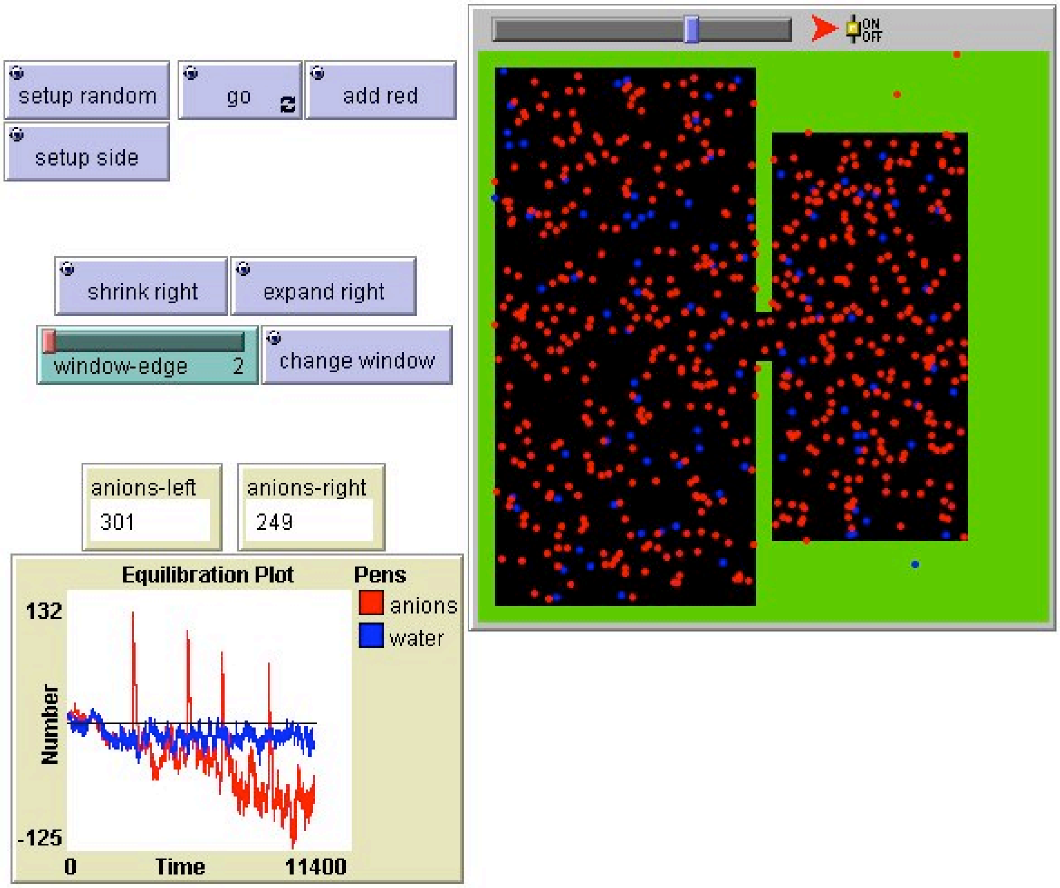
Figure 1. *SMV:Chem* screen for LeChatelier's principle experiment showing effect of a change in volume on the equilibrium compositions of the sample.

After the temperature change the animation shows the composition fluctuating with either one or two dimmers present and the rest monomers. The graph window shows the relative increase in the partial pressures of the species as the temperature is increased, with the partial pressure of NO_2 increasing more. Class discussion or homework questions ask students to consider what is shown in the animation that is not visible in the video of the experiment, which properties of a chemical equilibrium are correctly and which incorrectly shown by the animation, and how LeChatelier's principle could be used to explain the observed and portrayed shift in composition.

The features of *SMV:Chem* are an example of how the Multimedia, Modality, Signaling, and Interactivity design principles described by Mayer can be implemented in multimedia chemistry software. Our research on students' use of this software illustrates its effectiveness. Research on the *4M:Chem* prototype (Kozma, Russell, Jones, Marx, & Davis, 1996) showed a significant increase in college students' understanding of concepts related to equilibrium after a lecture using a unit of *4M:Chem* similar to the *SMV:Chem* unit illustrated in Figure 1. There was also a significant reduction in common equilibrium misconceptions. A more recent study (Russell, 2004) using *SMV:Chem* over the course of a semester showed significantly higher scores for students who attended lectures supplemented by *SMV:Chem* demonstrations and who used the software to do homework assignments than for students who were not exposed to the software or those who saw the software used in lecture but did not use it for homework.

A small study by Kozma (2000b) using the *4M:Chem* unit on gas-phase equilibrium indicates that specific features of the medium play a particularly important role in these results. In this study, students used a worksheet to guide their interactions with the software. One group had access only to the animation window; another group used only the video window; a third group used only the graph window; and a fourth group used all three windows. Each group had an audio narration customized to the visual features in that presentation. The group that received all three presentations had a narration that coordinated features across all of the representations. The animation group scored higher than the other groups on test items having to do with the dynamic nature of gas-phase equilibrium. The graph group scored highest on items dealing with relative pressures. The group that received all three media and the group that received video-only did not outscore the other groups on any of the items, indicating that video may not have provided students with information they needed to understand the concept and multiple representations may have exceeded students' capacity to process all of them simultaneously.

Connected Chemistry is another example of a multimedia project also targets the learning of difficult chemistry concepts (Stieff & Wilensky, 2003; http://ccl.northwestern.edu/netlogo/models/). The software is a collection of computer-based *simulations* of closed chemical systems that students can interact with in several ways. Each simulation focuses on a chemical concept such as factors effecting rates of reaction or LeChatelier's principle. Unlike *SMV:Chem* which uses "canned" animations, *Connected Chemistry* is written in NetLogo, a multi-agent modeling language, and it actually generates the graphics on the fly, in response to student input. The interface window of *Connected Chemistry* for the "Simple Kinetic 3" module is shown in Figure 2. The interface consists of three fundamental components: a graphics window for a nanoscale representation of the system, a plotting window for graphs of macroscopic properties of the system, and an area for setting system parameters and starting, pausing, restarting, and resetting the simulation. It does not display videos of the actual experiment, as does *SMV:Chem*, nor does it provide an audio narration of the various graphic representations it provides. The module in Figure 2 simulates the equilibrium distributions of a solute species and water molecules between two connected volumes as various parameters are adjusted. The graphics window displays visualizations for solute molecules shown as red circles (majority species) and water molecules shown as blue circles (minority species). As the simulation runs, all molecules in the graphics window are in rapid motion. The plotting window shows the difference in numbers of solute molecules in the right and left sides. Figure 2 shows five changes to a system that initially had equal left and right volumes and numbers of solute and water molecules on each side—first a decrease in volume of the right side followed by four additions each of 125 extra solute molecules to the right side. The excess of water in the left side (negative numbers in graph) is influenced only by the volume change. After each addition of solute species the equilibrium distribution changes to give a larger excess of solute species in the left side.



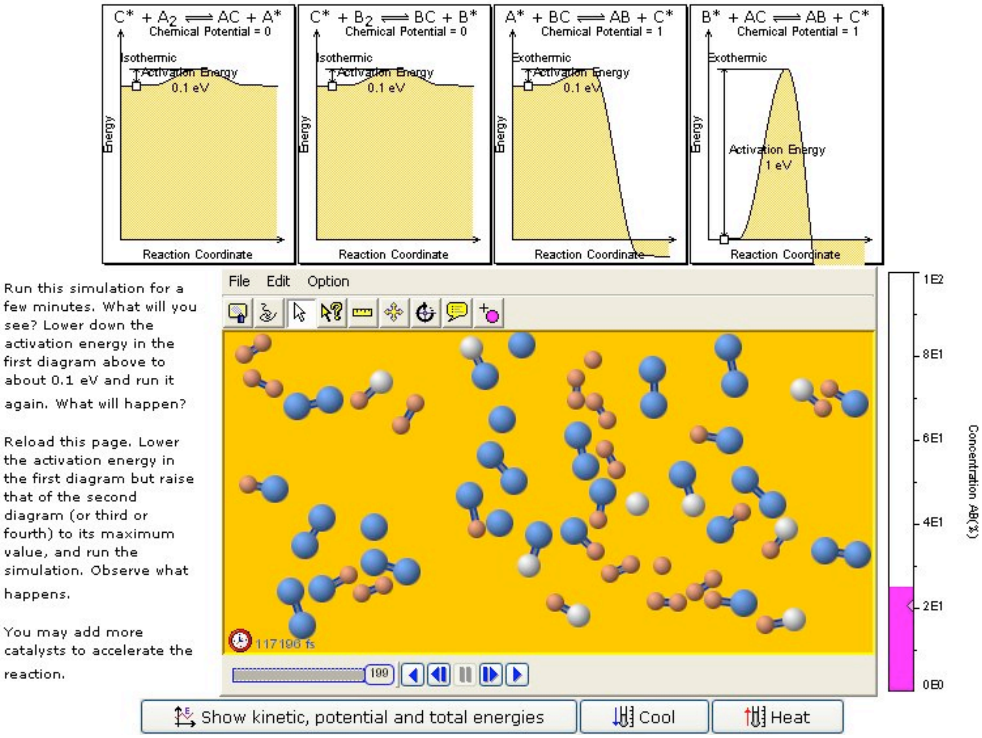
window-edge 2

anions-left 301

anions-right 249

Figure 2. Connected Chemistry interface window for Simple Kinetics 3.

Yet another multimedia software package designed to support the learning of difficult concepts in chemistry is *Molecular Workbench*. *Molecular Workbench* also uses advanced computational techniques to provide a variety of real-time, interactive simulations of chemical phenomena by adding sets of rules describing chemical reactions to a molecular dynamics modeling system (Xie & Tinker, 2004). All simulations display a two-dimensional molecular dynamics model with graphs of potential energy. The software has the flexibility to allow users to set most initial parameters including the atoms, their positions, velocities, and bonds as well as all potential energies parameters. As an example of one *Molecular Workbench* simulation, Figure 3 shows a snap shot of the computer screen as the simulation progresses for a homogeneous catalysis. As with *Connected Chemistry* and unlike *SMV:Chem*, *Molecular* a variety of topics are available at http://www.workbench.concord.org/modeler/index.html.



Run this simulation for a few minutes. What will you see? Lower down the activation energy in the first diagram above to about 0.1 eV and run it again. What will happen?

Reload this page. Lower the activation energy in the first diagram but raise that of the second diagram (or third or fourth) to its maximum value, and run the simulation. Observe what happens.

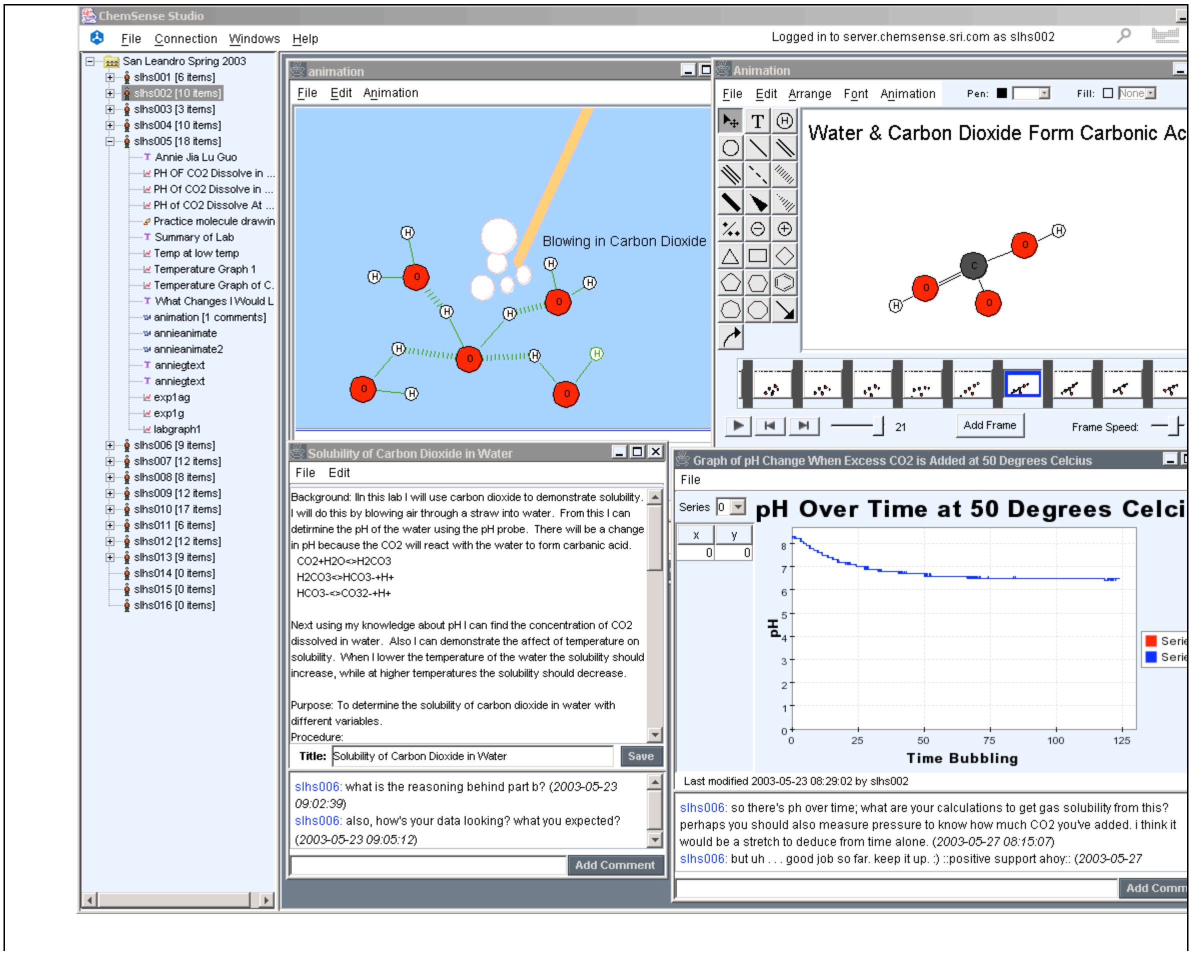
You may add more catalysts to accelerate the reaction.

Figure 3. ***Molecular Workbench*** **simulation of homogeneous catalysis for $A_2 + B_2$ _ 2 AB.**

Molecular Workbench does not provide narration or a video of the experiment as it appears on the lab bench as it is provided in *SMV:Chem*.

Multimedia to support laboratory investigation. While *SMV:Chem* and other environments described above are applications of cognitive theory to support student learning of chemical concepts and principles, *ChemSense* is an application of situative theory designed to support student inquiry in the wet lab. With *SMV:Chem,* students *manipulate* and *observe* multiple representations of pre-specified chemical experiments. On the other hand, the *ChemSense* environment offers students an ensemble of tools with which they can *create and analyze* representations of their own experiments (Schank & Kozma, 2002). An essential component of the *ChemSense* design is that the tools are used within social (i.e., students working collaboratively) and physical (i.e., working in the wet lab) contexts to investigate, analyze, and discuss chemical phenomena. Within these contexts, students jointly conduct wet lab experiments and use multiple representations to analyze, discuss, and understand their goals, results and conclusions.

Figure 4 shows the basic layout of *ChemSense*. The environment contains a set of tools – drawing, animation, graphing, and text tools – for creating and viewing representations, and a commenting feature for peer review. A web interface, called the *ChemSense Gallery*, is also available for viewing and commenting on work, and managing groups and accounts. Several examples of student-generated items can be seen in Figure 4. At the top of the window are two animations that students created to show the process of a gas – specifically, carbon dioxide – dissolving in water. To create these animations, students constructed individual frames that stepped through the breaking of bonds between the carbon, oxygen, and hydrogen, and the subsequent formation of carbonic acid, H_2CO_3 (aq). Below and to the right of the animations is a display of a dynamic graph that shows student-collected data from an experiment on the change in pH of the solution as carbon dioxide is dissolved over time. This data was collected at the lab bench through the use of probeware (developed by Pasco Inc., Roseville, CA) and imported into *ChemSense*. Below the graph is a comment area where other students can submit and view comments and questions. (Every item in the workspace has its own personal comment area.) To the left of the graph is student-constructed description of the lab purpose, procedure, and findings.



Background: IIn this lab I will use carbon dioxide to demonstrate solubility. I will do this by blowing air through a straw into water. From this I can detirmine the pH of the water using the pH probe. There will be a change in pH because the CO2 will react with the water to form carbanic acid.

CO2+H2O<>H2CO3
H2CO3<>HCO3-+H+
HCO3-<>CO32-+H+

Next using my knowledge about pH I can find the concentration of CO2 dissolved in water. Also I can demonstrate the affect of temperature on solubility. When I lower the temperature of the water the solubility should increase, while at higher temperatures the solubility should decrease.

Purpose: To determine the solubility of carbon dioxide in water with different variables.
Procedure:

Title: Solubility of Carbon Dioxide in Water

slhs006: what is the reasoning behind part b? (*2003-05-23 09:02:39*)
slhs006: also, how's your data looking? what you expected? (*2003-05-23 09:05:12*)

Last modified 2003-05-23 08:29:02 by slhs002

slhs006: so there's ph over time; what are your calculations to get gas solubility from this? perhaps you should also measure pressure to know how much CO2 you've added. i think it would be a stretch to deduce from time alone. (*2003-05-27 08:15:07*)
slhs006: but uh . . . good job so far. keep it up. :) ::positive support ahoy:: (*2003-05-27*

Figure 4. The *ChemSense* tool set with navigation tree (left pane) and workspace containing sample high school student work on the process of carbon dioxide dissolving in water.

As an application of situative theory, *ChemSense* is designed to shape the way students think and talk about representations, physical phenomena, and underlying chemical entities and processes. For example, in considering the dissolving of carbon dioxide into water, students can use the animation tool to build a representation of this dynamic process. As they create their animation they are confronted with a set of decisions about how to represent their understanding of the dissolving process—What does a water molecule look like? What is the structure of carbon dioxide? What happens to the water and carbon dioxide structures as they meet? Which atoms are involved? How many are there of each kind? The *ChemSense* environment also gives students the means to coordinate these representations with observable phenomena using probeware. For example, students collect wet-lab data such as temperature or pH and import the data into *ChemSense*. They then can create and run two representations – a nanoscopic-level representation showing the underlying process, and a tool-generated representation (i.e., the graph) showing the change in observable properties. The purpose of using two representations that show parallel changes at the nanoscopic and physical levels is to support student discussions about what is happening at the nanoscale that determines the emergent properties of what they see on the lab bench.

ChemSense is used with curriculum units specially designed to support investigative activities and to scaffold student use of interconnected representations in order to ask questions, describe, explain, and argue about the chemical experiments they are conducting on the lab bench. In addition, the environment allows students to peer-review each other's work, by way of interlaced discussion and commentary. For example, a teacher may include an activity that asks students to review the work of other lab groups and ask questions related to the chemistry in their representations. As part of their assignment, each lab group is responsible for providing critical feedback on other students' work. Used appropriately, this function further supports the possibility for students to collectively arrive at new understandings of scientific concepts by asking students to probe other students' thinking (Brown & Campione, 1996; Scardamalia & Bereiter, 1994).

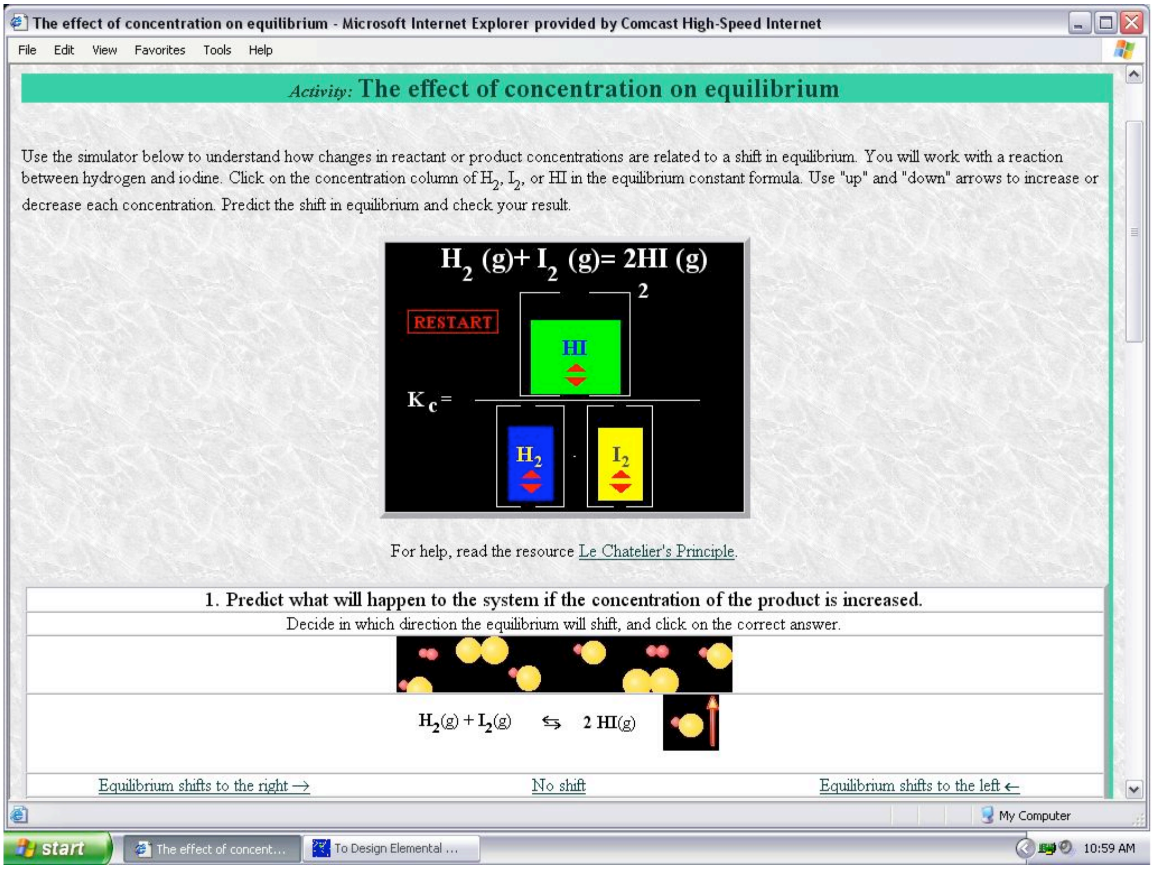
In a study (Schank & Kozma, 2002) of high school students using a *ChemSense*-based, 3-week unit on Solubility, we found that students who created more drawings and animations in *ChemSense* developed greater skill in using representations (i.e., "*representational competence*") and deeper understanding of geometry-related aspects of chemical phenomena in their animations. Analysis of videotapes of two high school groups working in the ChemSense environment showed that use of the tools prompts students to think more carefully about specific aspects of chemical phenomena to which they might not otherwise attend, such as the number of molecules involved in a reaction, the particular bonds created in the reaction, the bond angles, or the sequence of steps in a reaction. Throughout these collaborative sessions, students used the representations to both develop and reveal their understandings of chemical phenomena.

Another example of multimedia chemistry software that supports investigation is *ChemDiscovery* (formerly called *ChemQuest*). *ChemDiscovery* provides a technology-based inquiry-oriented learning environment (Agapova, Jones, Ushakov, Ratcliffe, & Martin, 2002). Rather than using lectures and worksheets as the primary instructional vehicles, *ChemDiscovery* features interactive web pages linked to activities, databases, and design studios and coordinates with hands-on laboratory activities. Students work in pairs or small cooperative learning teams with instructors functioning as coordinators and facilitators.

ChemDiscovery consists of eight projects or "quests" that can be used individually to supplement a traditional classroom or as a set to replace most of the traditional curriculum. Each project includes design activities such as those shown in Figure 5. In this example students can increase or decrease the relative concentration of one of the species involved in the equilibrium between hydrogen, iodine, and hydrogen iodide using the arrows on the bar for the selected species. Prior to making the change students are asked to predict if the equilibrium composition will shift and if so in which direction. After running this simulation students then predict the direction of change for a number of reactions that are represented both by symbols and by molecular representations. A typical *ChemDiscovery* classroom would have student teams working simultaneously on a range of activities that allows students to benefit from actions of their team as well as the others in the class.

What We Know About Multimedia Learning of Chemistry

As described above, recent years have seen a significant amount of development work in chemistry using the most advanced multimedia technologies, such as multi-agent-generated real-time animations of molecular systems. However, most of the research studies on multimedia in chemistry have been with older technologies, such as still pictures and simple, canned animations. Nonetheless, these studies shed light on the effectiveness of multimedia learning of chemistry.



Activity: The effect of concentration on equilibrium

Use the simulator below to understand how changes in reactant or product concentrations are related to a shift in equilibrium. You will work with a reaction between hydrogen and iodine. Click on the concentration column of H_2, I_2, or HI in the equilibrium constant formula. Use "up" and "down" arrows to increase or decrease each concentration. Predict the shift in equilibrium and check your result.

$H_2(g) + I_2(g) = 2HI(g)$

$K_c = \frac{[HI]^2}{[H_2] \cdot [I_2]}$

For help, read the resource Le Chatelier's Principle.

1. Predict what will happen to the system if the concentration of the product is increased.

Decide in which direction the equilibrium will shift, and click on the correct answer.

$H_2(g) + I_2(g) \leftrightarrows 2\,HI(g)$

Equilibrium shifts to the right → No shift Equilibrium shifts to the left ←

Figure 5. Design studio for ChemDiscovery equilibrium simulator.

A study by Noh & Scharmann (1997) examined the impact of molecular-level pictures on the acquisition of chemistry concepts and problem-solving skills. Groups of Korean high school chemistry students were randomly assigned to treatment and control groups and, over a 13-week period, were given 21 hours of chemistry instruction on concepts related to chemical equations, gases, liquids and solids, and solutions. As each concept was introduced, students in the treatment group received a series of still pictures of chemical phenomena, a total of 25 sets of materials over the period of the treatment. The pictures were a combination of macro-level representations (e.g., iconic drawings of containers under different amounts of pressure) and nanoscopic representations (e.g., cutaways of the containers showing different densities of molecules, as represented by 2-

D balls, moving about, as represented by trailing lines). Teachers used these pictures as part of their verbal explanations of concepts. Students in the control group received traditional expository instruction. Students were tested using two standard chemistry tests, the *Chemistry Conceptions Test* and the *Chemistry Problem-Solving Test*. Both tests used both items that employed molecular-level pictures of chemical systems as well as items that involved text or numerical responses. Students who received the pictorial treatment scored higher on the concept posttest than did students in the treatment group, while there were no significant differences between the two groups on the problem solving test. Differences in mean scores between the groups did not hold across the entire concept test but were due to significant differences on the Diffusion and Dissolution subtests, not on the Particle and State subtests.

In a study involving high school teachers from 12 different schools, Bunce and Gabel (2002) examined the impact of static nanoscopic, or “particulate”, representations used in three, 2-week modules on tests of chemistry concepts, including states of matter, solutions and bonding, and stoichiometry. The treatment group received instruction using three representations of matter—macroscopic (e.g., demonstrations of observable chemical phenomena), particulate (e.g., still pictures of chemical systems with molecules represented by 2-D structures composed of dots or circles representing elements), and symbolic (e.g., using chemical or mathematical symbols and equations). The control group used the same curriculum materials but received instruction using only the macroscopic and symbolic representations. The treatment group out performed the control group across the three modules on common teacher-made tests, consisting of items using each of the representational forms. However, the results were due primarily to significant differences on the first module, States of Matter, and to items on the test that used particulate representations. The study found differences that favored males over females in the control group but females did as well as males in the treatment group.

Ardac and Akaygun (2004) conducted a similar experiment with 8th-grade science students in Turkey. Students in the experimental group received interacted with a multimedia software program, *Chemical Change*, that allowed students to view simultaneous presentations at the macroscopic (i.e., video of experiments), symbolic (i.e., chemical equations), and molecular (i.e., molecular drawings and simple animations) levels. The student spanned 10 classes over a two week period and included topics such as Physical and Chemical Changes, Chemical Reactions, Conservation of Mass, as so on. Each student worked individually at a computer and their interaction was guided by a worksheet that asked them to explore a particular topic, interconnect the multiple representations, and respond to questions. Students in the control group received lectures on the same topics accompanied by equations and molecular drawings on the chalk board. Students were tested with true and false and multiple choice items. Some items used molecular-level representations; others just used text and equations. Students in the experimental group scored higher on the posttest items that used molecular representations. Students in the experimental group also displayed more particulate-level representations and showed more conceptual accuracy in a posttest interview than did control group students.

The effects of molecular-level animations were explicitly examined in several studies. Williamson and Abraham (1995) used such animations (i.e., molecules represented by dots bouncing around and interacting) with students in one of two sections of a university general chemistry course. Both sections received the same series of 10 lectures on concepts related to gases, liquids, solids, and solution reactions. The instructor used static pictures and chalk diagrams with both lecture sections. In the treatment section, the lectures were supplemented by a series of animations illustrating the concepts at a molecular level. A subset of students in the treatment group was also allowed to see the animations, multiple times if desired, and respond to worksheets in the computer lab during their discussion section meetings. There were no differences between the three groups on the course exam. However, there were differences between the control group and the treatment groups on tests specifically designed to assess students' understanding of the concepts included using molecular-level diagrams. Students in both treatment groups scored higher than students in the control group but there were no significant differences between the two treatment groups.

Sanger and Greenbowe (2000) examined the impact of animations and conceptual change strategies on students' conceptions of current flow in electrolyte solutions. In this 2 X 2 design, university students in one group received a lecture along with an animation accompanied by lecturer's narration showing the electrochemical processes occurring in a galvanic cell at the nanoscopic level with a focus on the chemical half-reactions occurring at each electrode and the transfer of ions through a salt bridge. Students in the other lecture section saw only static chalkboard drawings of the process. Half the students in these groups also received a conceptual change strategy that confronted typical misconceptions while the other half did not. Students were tested using algorithmic, visual, and verbal test items on both an immediate and a delayed post test. There were no significant differences between any of the treatment and control groups on the algorithmic or visual test items. There was, however, a main effect in favor of the conceptual change strategy (but not one for the use of animations) on the verbal items on both the immediate and delayed post-tests. There was also an interaction between the animation and conceptual change treatments for these items on the immediate post-test such that students who did not receive the conceptual change strategies scored higher with the animations than those students who received the conceptual change strategies but not the animations.

In a study by Yang, Andre, and Greenbowe (2003), university students who received a lecture on chemical reactions that occur inside a battery also received animations accompanied by lecture narrations. Students in another section received the lecture only accompanied by static diagrams. On a test of topic knowledge, students in the animation group outperformed the students receiving the static diagrams. However on a test of transfer, there was an interaction such that students with higher spatial ability who received animations performed better than students with low spatial ability or those that did not receive the animations.

In an experiment by Sanger, Phelps, and Fienhold (2000), students in the treatment group viewed three times an animation accompanied by narration that showed representations at both macroscopic (i.e., a can being heated, sealed, and crushed upon cooling) and nanoscopic levels (i.e., numbers of 2-D balls representing molecules moving around both inside and outside the can, more quickly or slowly). Students in both the treatment group and the control group received a lecture on gas behavior and observed a physical demonstration of the can-crushing experiment. Students in the treatment group scored significantly higher on measures related to understanding a similar demonstration.

In another experimental study (Sanger & Badger, 2001), students in the treatment group received instruction on and demonstrations of miscibility of polar, non-polar, and ionic compounds supplemented by both molecular-level animations of inter-molecular attractions, as well as shaded 2-D pictures of electron density plots ("eplots") that used color to show the polar (i.e., charged) regions of various molecules. Students in the control group received only instruction and demonstrations. Students in the treatment group scored significantly higher on an experimenter-constructed test in which students were asked to identify polar molecules not discussed in the instruction, make predictions about the miscibility of compounds, and explain their answers.

There is a new technology—*interactive molecular modeling graphics*—that is increasingly being used by professional chemists (although we did not happen to observe this technology being used in our study of practicing chemists (Kozma, et al., 2000)). Molecular models are computer constructions of 3-D molecular structures projected on a 2-D computer screen that consist of space-filling, ball-and-stick, or wire-frame representations of a single, sometimes very complex, molecule of a species (Francoeur, 2002). With this technology, the user can construct a model, rotate it through 3-D space, examine energies, and measure angles and the lengths of bonds. This technology is coming to be used rather widely in chemistry education at the university level (Bragin, 1996; Cody & Wiser, 2003; Jones, 2001; Kantardjieff, Hardinger, & Van Willis, 1999; Martin, 1998; Montgomery, 2001) and occasionally even at the high school level.

A few studies have been conducted on the effect of this new technology on learning. Dori and her colleagues (Barnea & Dori, 1999; Dori & Barak, 2001) have used computer models with high school students in Israel as part of a chemistry program to improve students' understanding concepts of molecular bonding and structure, their spatial ability, and students' perceptions of the concept of a model. In the first study, students in the experimental group worked in pairs to conduct a series of investigations using a workbook and molecular modeling program. Under the guidance of the workbook, students selected different molecules from a library of models, displayed them in different representational modes, rotated the models in 3-dimensional space, and measured the bond lengths and angles. As part of their investigations, students had to decide on what geometric shape of the models, along with other structural properties. Students in the control group studied the same topics in the traditional way using plastic models rather than computer models. Students in the experimental group scored higher than those in the control group on measures of their understanding of structure and bonding. Students in both groups scored higher from pre to post on standard measures of spatial ability, the experimental group significantly more so. Experimental group students also scored higher on measures of the concept of a model (i.e., "model perception") in which students were asked to describe models and how they are used. Experimental group females improved their model perception more than control group females in understanding ways to create models and in the role of models as mental structures and prediction tools. In the second, parallel study students in the experimental group scored higher than the control group on tests that measured students understanding of isomers in organic compounds. They scored higher on all types of test items, those that involved graphics, text, and a combination of graphics and text. As with the earlier study, experimental group students scored higher than control group students on measures of the concept of model.

The Limitations of Research on Multimedia Learning of Chemistry

In general, the findings from the research studies that we have reviewed support the use of multimedia to teach concepts and principles in chemistry. With one exception (Sanger & Greenbowe, 2000) multimedia was more effective than the alternative—the use of still pictures and animations of molecular systems, and interactive models and electron density plots of single molecules all proved to be effective. However, there are some important limitations in this research.

Unlike the experiments done in Mayer's cognitive laboratory, all of these studies were done within regular chemistry classroom settings. Classroom research is an important way to establish external validity of findings when using multimedia. At the same time, these studies typically lack the kind of experimental control that is needed to specifically support one design principle or another. For example, there were problems with treatment fidelity in several studies. In the Sanger and Badger study (2001) dynamic animations were used along with static electron-density plots in the treatment group making it difficult to attribute the effect to one or the other treatment. Observations of lectures in the Noh and Scharmann (1997) study of static pictures versus traditional instruction found that control-group lecturers were using chalk board diagrams as part of their instruction. Similarly, control group students in the Ardac and Akaygun (2004) study received molecular-level drawings during lecture. There are other general problems related to experimental control, such as the failure to control the specific verbal content across lectures or the specific timing and function of verbal content, relative to the presentation of visual content. While these problems are inherent with classroom research it means that conclusions can not sort out the extent to which the effects due to application of a specific principle, such as the multimedia principle or the signaling principle.

In several studies the findings favoring multimedia were limited to specific kinds of topics, such as results favoring static pictures for units on states of matter but not bonding or stoichiometry (Bunce & Gabel, 2002) and for diffusion and dissolution but not particulate matter or states of matter (Noh & Scharmann, 1997). Most of the studies used tests that were specially designed to include molecular-level diagrams. In the Bunce and Gabel (2002) and the Ardac and Akaygun (2004) studies, differences between the experimental and control groups were limited to those test items that used molecular-level diagrams. The findings of all these studies, and their limitations, have implications for cognitive theory, instructional design and classroom practice, and future research.

Implications of the Research for Cognitive Theory

Even with their limitations, the findings of these studies generally support the cognitive theory of Mayer and others as it applies to chemistry learning. However, they also raise additional questions that should be pursued in future research, questions that if answered might help us better understand how multimedia supports the learning of concepts and principles. For example within the visual channel, are there differences among different kinds of visual symbol systems (e.g., graphs, animations, etc.) in their support of learning? Do different representations support the learning of different kinds of concepts and principles? The Kozma (2000b) study of *4M:Chem* found that students who used the animations did better on test items related to the dynamic nature of gas-phase equilibrium and students who used graphs of relative pressures over time did better on items related to partial pressures. Noh and Scharmann (1997) found that even static pictures of dynamic systems did better on portions of the test related to dynamics (i.e., diffusion and dissolution) but they did not help on less dynamic concepts (i.e., particle and state). We need to further refine our cognitive theories about how the surface features or properties of specific representations (such as motion, color, shape, etc.) and their syntax (i.e., rules for putting these features together in certain ways) can support learning of concepts with certain underlying characteristics related to geometrics, dynamics, rate, and so on. These refinements of cognitive theory require further research (see below).

By intent, theory and research have a symbiotic relationship. Sometimes research results allow us to refine or modify our theories; sometimes theory influences the type of research that is done. Cognitive theory has had a strong influence on the kind of research done on multimedia learning of chemistry. Almost all of the studies we reviewed focused on the use of multimedia to support the learning of chemical concepts and principles. Few studies focused on the use of representations to support the goal of learning chemistry as a process of investigation. The exceptions to this situation are the Kozma (2000a) study of university inorganic chemistry students working with modeling software in their laboratory course and the Schank and Kozma (2002) study of high school students using *ChemSense* to support their laboratory investigations. If we are going to expand our research base to include studies focus on the outcome goal of learning science as a process of investigation, we need to expand our theoretical base for multimedia learning to include situative theory which focuses on the use of representations to support investigative practices.

Implications of the Research for Instructional Design and Classroom Practice

In general, the results of the research that we reviewed justify use of multimedia in chemistry instruction, when the goal is to teach concepts and principles. Multimedia seemed to be effective for lower secondary, upper secondary, and college chemistry students. We identified instances in which the use of still pictures of molecular systems to supplement lectures was successful in teaching concepts related to states of matter, diffusion, and dissolution. We found studies in which animations accompanied by narrations were successful in teaching concepts related to equilibrium, reaction chemistry, electrochemistry, and miscibility. We found studies in which the use of molecular models supported students' understanding of structure and bonding. Several significant multimedia development projects, such as *SMV:Chem, Connected Chemistry,* and *Molecular Workbench*, are providing instructors and instructional designers with new technological resources to bring multimedia into the chemistry classroom in support of conceptual understanding. However we are not able to say, given the state of research, for which topics or students it is best to use animations versus still pictures or models. Nor can we say how these various media can be used together and when it is best to do so. For the time being, all of these practical issues are left up to the art and judgment of instructors and instructional designers.

If the goal is to teach chemistry as a process of investigation, we can say even less, based on research done to date. Situative theory would argue for the use of various representations in the context of laboratory investigations, using them to ask questions, plan experiments, carry out procedures, analyze data, and present findings. New software systems, such as *ChemSense* and *ChemDiscovery*, provide instructors with powerful tools to support students' investigations. But there is little research so far that helps guide instructors and instructional designers on how to effectively integrate these tools into classroom and laboratory activities.

There are, however, many studies that have implications for student assessment. Almost all of the studies that we reviewed used specially designed tests which measured students' understanding in new ways and measured new goals for chemistry learning, such as increasing students' abilities to use appropriately diverse forms of representations in problem solving, as they are used by experts. Indeed, multimedia applications had the greatest effect on test items of this sort. These findings argue for the integration of still pictures, animations, models, and other multimedia into the tests and examinations of chemistry courses and the widespread availability of new technologies makes the use of these new tests more feasible.

Implications for research

As cited above, there is an urgent need for more research in the area of multimedia learning in chemistry. There is a need for carefully controlled cognitive experiments that supplement classroom studies. These experiments could carefully analyze the effects of static pictures versus animation versus molecular models on the learning of various types of chemical concepts and principles. They could examine for which concepts it would be most effective use models of single molecules, animations of a single molecular reaction, or simulations of entire systems. They could examine a broader range of symbol systems that include chemical formulae and equations, graphs, and instrument print outs and displays as they might influence the learning of one type of concept or another. And there is a need for research that looks at the effectiveness of using these various symbol systems together.

A number of studies that we examined identified aptitude X treatment interactions (ATIs). Bunce and Gabel (2002) found an ATI favoring females when using stills and Barnea and Dori (1999) found one favoring females when using molecular modeling software. Yang, Andre, and Greenbowe (2003) found an ATI that favored high spatial ability students when using animations. There was also a treatment X treatment interaction (Sanger & Greenbowe, 2000) and numerous treatment X measurement interactions (Noh & Scharmann, 1977; Bunce & Gabel, 2002: Williamson & Abraham, 1995; Sanger & Greenbowe, 2000; Yang, Andre, & Greenbowe, 2003). While ATIs were not systematically examined across studies and no consistent patterns were established, the number of ATIs that emerged argues for including gender, spatial ability, and measurement variables as regular features in the design of future multimedia studies in chemistry.

There is also a significant need for research that focuses on the process of laboratory investigation and how it is that the use of various symbol systems and multimedia environments facilitates investigative practices. There is a need to extend research beyond the lecture hall or computer lab into the chemistry laboratory. New assessments must be designed and used that measure investigation practices and related skills, such as representational competence (Kozma, et al., 2002). In order to integrate cognitive and situative perspectives, research studies must examine the relationship between learning investigative practices and the development of chemical understanding.

Finally, there is a need to systematically evaluate large multimedia projects, such as *SMV:Chem, Connected Chemistry, Molecular Workbench, ChemSense,* and *ChemDiscovery*. Significant investments have been made in these projects (typically by the National Science Foundation) and more research is needed as these projects are scaled beyond their use by the initial faculty members and teachers affiliated with the development projects.

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Glossary

Molecular models or *interactive molecular modeling graphics*: Computer software programs which display the arrangement and bonding of atoms within a molecule. These programs typically allow users to construct molecules (or view molecules constructed by others) and operate on these structures by rotating them in 3-dimentional space, measuring bond lengthens and angles, and viewing them in different forms (such as space filling or wire tube).

Nanoscopic: Term used to refer to structures measured in nanometers (usually 0.1-100nm) and of a size below that which can be seen with the aided eye.

Representation: In this context, the word refers to *external* symbols or symbolic structures that refer to other objects or events. These external representations are distinguished from internal, or mental, representations and are sometimes referred to as *inscriptions* (see Roth & McGinn, 1998). In chemistry, representations often refer to entities or processes that can not be observed directly (such as atoms, molecules and reactions) and can take a variety of forms (such a structural diagrams, equations, etc.).

Representational competence: A set of skills and practices that allow a person to use a variety of representations, singly and together, to think about, communicate, and act on aperceptual physical entities and processes, such as molecules and their reactions (see Kozma & Russell, 1997).

Simulation: In this context, the word refers to computational environments that represent a chemical system composed of large numbers of molecules, usually by a number of clustered balls or dots (representing molecules) that move about, collide, and react. A simulation might allow the user to change parameters of the system (such as temperature or concentration of a molecular species) built into the computational model and observe the impact of the change on chemical reactions within the system.

Situative Theory: A theory that postulates that the learning and understanding practices of a community are influenced by the physical and social characteristics of a specific setting and, in turn, the characteristics of the setting are influenced by the community of practice (See Greeno 1998).