

# **Learning Chemistry through Design and Construction**

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## **Introduction**

Imagine students learning chemistry not only by reading about it, but by designing and constructing the world from elementary particles according to chemical principles. Because introductory chemistry subjects focus primarily on analysis, the design aspect of chemistry is not often encountered by students until they take advanced subjects. Yet the mental processes involved in thinking through the design of an experiment or a molecule can be powerful learning experiences. This paper will discuss the role of four types of computer-based design activities in introductory chemistry:

- Design of simulated laboratory experiments
- Construction of computer models of molecular structures
- Design and construction of molecules and crystals from elementary particles
- Design and construction of solutions

## **Design of simulated laboratory experiments**

Many of the activities students complete in their coursework are “school activities,” activities conducted only in classroom settings. Seldom are opportunities to carry out more authentic science activities available. However, when asked to design their own experiments and control variables, students must think like scientists. Such authentic experiences are difficult to provide and to monitor in large general chemistry classes. However, multimedia computer-based simulated laboratory experiments can give students the opportunity to design and carry out many experiments in chemistry in a short period of time (Figure 2).<sup>1</sup> The general chemistry laboratory at the University of Northern Colorado was redesigned to incorporate units from the *Exploring Chemistry* multimedia software. This software integrates chemistry content with moving digital video images of chemical reactions and allows students to design experiments by selecting conditions for reactions, predicting the result, and then seeing what happens.<sup>2</sup>

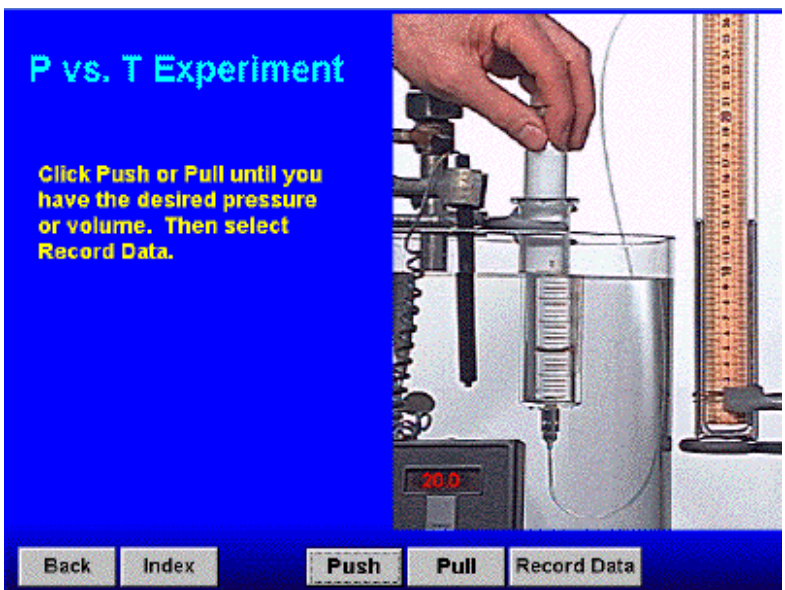


Figure 2. In this *Exploring Chemistry* simulation, students change the temperature of a gas sample and measure the resulting pressure. The collected data can then be plotted in a variety of ways.

The *Exploring Chemistry* lessons have been found to enhance student learning of concepts and laboratory techniques. In one study 21 students who completed multimedia equilibrium simulations that required them to design experiments scored significantly higher on an achievement test on equilibrium concepts than 49 students who had completed hands-on laboratory experiments on equilibrium.<sup>3</sup> In a second study 26 students completed multimedia simulations that required them to select a remote site, set up simulated equipment, collect an air sample and analyze it with a spectrometer. Two weeks later these students and 22 students who had completed an unrelated hands-on activity during the same time period were observed using the spectrometer in the laboratory. The students who had completed the simulation made one-third as many errors and took significantly less time to complete the procedure than did the students who had not experienced the simulation. The students who had worked with the simulated spectrometer tended to begin using the spectrometer as if they had used it before, consulting the instructor or manual only if they ran into a problem, while the other students tended to ask for help first.<sup>4</sup>

### **Design and construction of computer models of molecular structure**

Chemistry is a science at two levels—the macroscopic and the molecular—and design activities can be carried out at both levels. Because even university students have difficulty comprehending the particulate state of matter,<sup>5</sup> introductory chemistry at the University of Northern Colorado was reorganized to give students a foundation in molecular structure on which they can build understanding of topics such as stoichiometry and nomenclature.<sup>6</sup> In this approach, students begin by learning about atomic structure, then progress to the structure of molecules before studying the bulk properties of matter. Students use a molecular-modeling program such as *HyperChem*<sup>7</sup>

or *WebLab ViewerPro*<sup>8</sup> to construct molecules and view shapes, bond angles, and electron density (Figure 1). Once students feel comfortable with the structures of molecules, topics such as stoichiometry and equilibrium can be taught from the viewpoint of the molecular level of matter.



Figure 1. The red shading in this electrostatic potential diagram of methanol,  $\text{CH}_3\text{OH}$ , created in *WebLab ViewerPro* shows that electron density near the oxygen atom (red) is greater than that near the carbon atom (gray).

Using molecular modeling software allows students to learn about topics such as molecular shape and polarity in an inquiry mode. Instead of being told the rules governing molecular shapes, students can *develop* the rules by building and optimizing the structures of different molecules. They can also discover the effect of lone pairs on bond angles and see how differences in electronegativity affect the distribution of electrons in bonds and molecules.

Hands-on models can also be used to construct molecular models. In fact, a study of student achievement showed no difference in the learning of topics related to the three-dimensional nature of molecules between students using hand-held molecular models and those using a computer-based modeling program. However, when students were surveyed, they reported that they would prefer having both learning environments. They found that the hand-held models offer a better sense of three-dimensional features, as they can be felt as well as seen, and a set of related structures can more easily be compared in three dimensions. However, computer modeling programs offer students the opportunity to study bond angles, allow for the effect of lone pairs on bond angles, produce optimal structures, and show structures in different renderings (ball-and-stick, space-filling, stick, line, and dots). Molecular modeling software also gives students experience in the use of a valuable research tool. Programs that allow students to rotate and view preexisting molecules, but not to build molecules, provide some of these features, but do not allow the design and inquiry activities that are the strength of this approach.

### **Design and construction of molecules and crystals from elementary particles**

*ChemQuest: Chemistry for the Information Age*, is a computer-based chemistry curriculum that is being developed at the University of Northern Colorado with support

from the National Science Foundation. The curriculum emphasizes chemistry as a fundamental science within an environmental context and uses computer models and exercises to support and enhance students' mental models.<sup>9</sup> In this interactive inquiry-based learning environment students design and construct nuclei, atoms, molecules, crystals and eventually complex systems such as equilibrium systems and water treatment plants. Information is sought by students as needed to complete the assignments and to solve environmental problems.

The curriculum uses linked web pages organized around a series of learning scenarios that involve students in exploring the nature of matter using scientific methodology. As an example, students "construct" molecules and crystals on the computer, then predict and verify their properties and environmental consequences. The software includes activities, resources, chemistry databases, problems and exercises, and three-dimensional modeling capabilities (Figure 3).

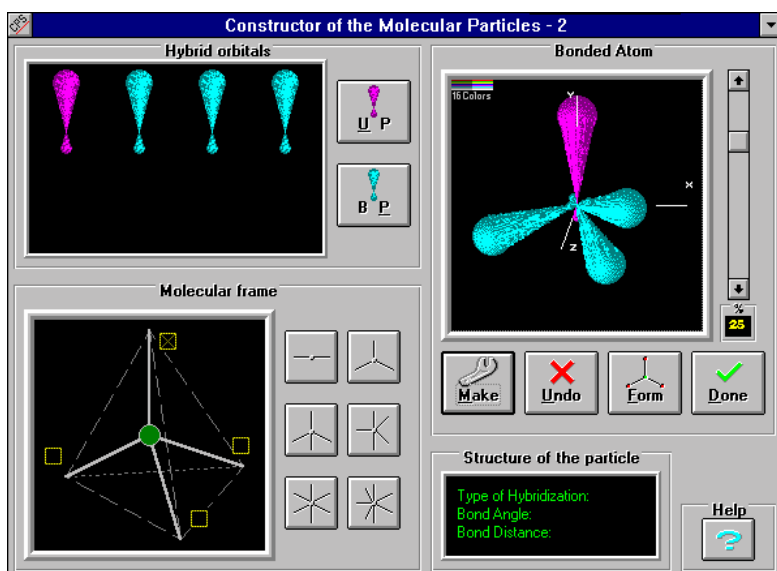


Figure 3. This *ChemQuest* activity allows students to design the shape of a simple molecule from a “toolkit” of bonding pairs and lone pairs of electrons. Both the molecular shape or the complete electronic geometry, as shown here, can be viewed and rotated.

The *ChemQuest* approach is based on collaboration in which student and teacher become partners in inquiry. By allowing students to work together to construct and evaluate their own models of matter and providing opportunities for active cooperative learning we can provide them with an interactive-constructive learning environment.<sup>10</sup> Instead of the instructor lecturing, students are working in small groups, using computer tools and hands-on equipment to solve problems and design chemical systems.

Calculations also involve design experiences. Students design their own problem-solving algorithms using simple spreadsheet routines with guidance available at every step. The

difference between this scheme and commercial problem-solver programs is that the commercial programs normally present algorithms that have already been completed, whereas in this scheme students develop their own algorithms.

The *ChemQuest* model differs from most others in that it uses information technology in a central, rather than supplemental fashion, with lectures and text fulfilling a supportive role. To date, evaluation of the curriculum has been carried out only in secondary schools. In a study of *ChemQuest* classrooms two teachers spent nearly equal amounts of time facilitating (38%) and lecturing (40%). In their traditional classrooms the same two teachers spent 4.5 times more instructional time lecturing (58%) as they did facilitating (13%).<sup>11</sup> Students were more likely to be engaged by their assignments when using the *ChemQuest* curriculum than they were in a lecture setting and the achievement of *ChemQuest* students compared favorably with national norms.

### **Design and construction of solutions**

Design activities that allow students to construct complex molecular systems are now available with the general chemistry textbook used in our program.<sup>12</sup> A CD devoted to molecular visualization created by Roy Tasker and the Cadre Design team at the University of Western Sydney includes a series of design simulations.<sup>13</sup> The simulations provide an electronic learning environment that allows students and their instructors to build connections between the observable and particulate levels of matter and also between these two levels and the symbolic representations of chemical phenomena. In this innovative approach students view video of an actual chemical reaction, then design their own molecular representations of these solutions. They can then compare their design with an expert design.

An example is the study of the reaction between zinc metal and solid iodine in water (Figure 4). Students view a motion video of the solution turning dark brown and bubbles forming. The white product is then separated. Students must construct at the particulate level the solid zinc and iodine reactants, the solution, and the product. As they do this, they discover how the reaction stoichiometry determines the maximum amount of product that can be formed.



Figure 4. In this simulation from the *Chemistry: Molecules, Matter, and Change* Visualization CD students construct a reaction mixture in aqueous solution by selecting and dragging solvent molecules and appropriate reactant, intermediate, and product species into the container on the left. They also watch a video of the reaction.

### Conclusions

Introductory chemistry learning environments that promote the use of design activities can provide students with opportunities to develop authentic scientific inquiry skills. They may also help students link chemical phenomena at the macroscopic level with events at the particulate level. Computer software and simulations can facilitate the introduction of design-based learning experiences into general chemistry.

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