LEARNING

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Enhancing Undergraduate Students' Chemistry Understanding Through Project-Based Learning in an IT Environment

MIRI BARAK
Center for Educational Computing Initiatives, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

YEHUDIT JUDY DORI
Department of Education in Technology and Science, Technion, Haifa 32000, Israel, and Center for Educational Computing Initiatives, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

ABSTRACT: Project-based learning (PBL), which is increasingly supported by information technologies (IT), contributes to fostering student-directed scientific inquiry of problems in a real-world setting. This study investigated the integration of PBL in an IT environment into three undergraduate chemistry courses, each including both experimental and control students. Students in the experimental group volunteered to carry out an individual IT-based project, whereas the control students solved only traditional problems. The project included constructing computerized molecular models, seeking information on scientific phenomena, and inquiring about chemistry theories. The effect of the PBL was examined both quantitatively and qualitatively. The quantitative analysis was based on a pretest, a posttest, and a final examination, which served for comparing the learning gains

Correspondence to: Yehudit Judy Dori; e-mail: yjdori@tx.technion.ac.il

of the two research groups. For the qualitative analysis, we looked into the experimental students' performance, as reflected by the projects they had submitted. In addition, "think aloud" interviews and observations helped us gain insight into the students' conceptual understanding of molecular structures. Students who participated in the IT-enhanced PBL performed significantly better than their control classmates not only on their posttest but also on their course final examination. Analyzing the qualitative findings, we concluded that the construction of computerized models and Web-based inquiry activities helped promote students' ability of mentally traversing the four levels of chemistry understanding: symbolic, macroscopic, microscopic, and process. More generally, our results indicated that incorporating IT-rich PBL into freshmen courses can enhance students' understanding of chemical concepts, theories, and molecular structures.   © 2004 Wiley Periodicals, Inc. *Sci Ed* **89:**117–139, 2005

INTRODUCTION

Looking at students' achievements in mathematics and science in over 40 countries at the elementary, middle, and high school levels, the Trends in International Mathematics and Science Study (TIMSS) (Schmidt et al., 2001) reported that countries such as the United States and Israel lag behind other countries, especially by the end of secondary school. The study findings indicate that the learning materials and the ways they are taught make the difference. The key to improving mathematics and science teaching, according to the TIMSS researchers, is the curriculum in the broad sense, namely, the standards, textbooks, sequence, and depth of the content taught. On the basis of the TIMSS findings, the authors conclude that creating challenging curricula across all years of schooling for all students is of utmost importance (Schmidt et al., 2001).

A prominent means to enhance science curricula is project-based learning (PBL). This teaching method is characterized by authentic investigation, the production of an end product, collaboration among peers, and the use of technology to support the process of inquiry (Klein & Merritt, 1994; Krajcik, Czerniak, & Berger, 1999; Polman & Pea, 2001). Numerous studies present innovative development of project-based courses for K–12 students (Barab et al., 2000; Dori, 2003a; Dori & Tal, 2000; McDonald & Czerniak, 1994; Schneider et al., 2002; Tal & Hochberg, 2003). Other studies report the integration of project-based science into pre- and in-service science teachers' courses (Dori, 2003b; van Zee, Lay, & Roberts, 2003; Windschitl, 2003). There is, however, less evidence of PBL and its effect on basic science courses in higher education.

This paper describes the effect of integrating IT-enhanced PBL into three undergraduate chemistry courses. The research was conducted at the Department of Chemistry at the Technion, Israel Institute of Technology. The research goal was to investigate students' learning outcomes and their ability to traverse the various chemistry understanding levels. The experimental students volunteered to engage in home assignments of inquiry-based learning through a project that included constructing computerized molecular models. The research findings are presented and discussed in four sections. First, we present the students' learning outcomes through statistical analysis of their pretest, posttest, and final examination scores. Second, we analyze the students' ability to mentally traverse the four levels of chemistry understanding, as reflected in their projects. Third, we present the content analysis of the students' projects. Last but least, we describe a case study that exemplifies the students' learning process while using computerized molecular modeling (CMM) as a tool to construct models of complex molecules as part of their project. On the basis of our findings we argue that PBL encourages understanding of chemical concepts, theories, and molecular structures.

THEORETICAL BACKGROUND

In this section we focus on three subjects related to our research: PBL, applications of the Internet to science education, and the four levels of chemistry understanding.

Project-Based Learning

Project-based learning has been defined in the educational literature in a rather broad sense. In his review of research on problem- and project-based learning, Thomas (2000) found five criteria for identifying characteristics of PBL:

1. *Centrality*: PBL-type projects are central to the curriculum.
2. *Driving question*: The projects should focus on questions or problems that "drive" students to encounter (and struggle with) the central concepts and principles of a discipline.
3. *Constructive investigations*: The central activities of the project must involve the construction of knowledge by students.
4. *Autonomy*: Projects are student-driven to some significant degree.
5. *Realism*: Pojects are realistic or authentic, not school-like.

Garrison (1999) and Thomas (2000) are among the few researchers who have described PBL studies with undergraduate students. Garrison (1999) described experiences of a project-based distance-learning course, where students learned, refined techniques, and worked toward conceptual understanding of various finance and accounting topics. Thomas (2000) gave examples of problem-based learning models for medical students to help them improve their diagnostic skills through working on ill-structured problems.

Other educational studies on PBL included cooperative projects done by undergraduate students (Smith, 1998), inquiry projects conducted by pre-service secondary teachers (Windschitl, 2003), and project-based science (PBS) with elementary, middle, and high school students (Schneider et al., 2002). PBS, which has been studied quite intensively (Barak & Raz, 2000; Krajcik, Czerniak, & Berger, 1999; Marx et al., 1997; Tinker, 1996), is an approach that makes extensive use of student-directed scientific inquiry supported by technology and collaboration. In PBS environments, as in PBL in general, students are engaged as active participants in the learning process, setting their own learning goals and forging meaningful relations through their experiences, as they investigate real-world issues (Barab & Luehmann, 2002). PBS learning models typically have at least four essential components: (1) a driving question that organizes a long-term, authentic investigation or design project; (2) the production of tangible, meaningful artifacts as the end products of the learning activity; (3) collaboration with any subset of a learner's community, including peers, teachers, or members of society; and (4) the use of a cognitive tool, such as the Internet, to support the process of inquiry (Blumenfeld et al., 2000; Krajcik, Czerniak, & Berger, 1999).

Internet Applications in Science Education

Over the past decade, science educators have been engaged in experimental projects that focus on the integration of the Internet and the World Wide Web as an additional medium for teaching and learning. Information and communication technologies facilitate world-wide contacts between teachers and students, removing time and geographical barriers. The Internet is used as a source of scientific data and theoretical information (Murov, 2001).

Among its many applications, the Web serves as a tool for designing new learning environments (Barak & Rafaeli, 2004; Donovan & Nakhleh, 2001; Eylon 2000), integrating virtual models (Kozma & Russell, 1997), and creating learning communities (Gordin et al., 1997; Sudweeks & Rafaeli, 1996). Judicious use of these technologies can boost learning that is adapted to the abilities of each student, and enhance higher order thinking skills.

The Internet offers a viable means to support authentic science projects (Barab et al., 2000; Barab & Luehmann, 2002; Linn, 2000; Songer, Lee, & Kam, 2002). An important challenge in leveraging technologies to enhance innovative science teaching and learning is to determine how to design curricula that effectively integrate the use of these tools in a coherent and authentic way (Barab & Luehmann, 2002). Examples of innovative K-12 projects that have integrated technology into science classrooms include Global Learning and Observations to Benefit the Environment—GLOBE (Finarelli, 1998), Knowledge Integration Environment—KIE (Linn, 2000), Kids as Global Scientists—KGS (Songer et al., 2002), LabNet (Ruopp et al., 1993), and Web-based Inquiry Science Environment—WISE (Linn, Clark, & Slotta, 2003). However, research concerning the assimilation of PBL in higher education is less prevalent.

The Internet has rapidly emerged as an important tool for teaching science in higher education. Indeed, the number of chemistry courses that incorporate student use of the Web has increased (Foust et al., 1999; Donovan & Nakhleh, 2001; Dori, Barak, & Adir, 2003). Discovering the scope of information available over the Web and how to use it should be part of the undergraduate education of every chemistry student (Murov, 2001). Along this line, this study investigated the integration of PBL in undergraduate chemistry courses using CMM tools and the Internet as the learning environment.

Chemistry Understanding Levels

While teaching the properties of substances and how they react, chemistry educators initially identified three levels of understanding: macroscopic nature of matter, particulate nature of matter, and the symbolic representations of matter (Bunce & Gabel, 2002; Gabel, 1998; Johnstone, 1991). The macroscopic level refers to the sensory/visible phenomena that can be seen with the naked eye. The particulate nature of matter refers to the microscopic level, which deals with atoms, molecules, and ions and their spatial structure. The symbolic representation refers to chemical formulae and equations. In addition to these three levels, Dori and Hameiri (2003) suggested a fourth level—the process level, at which substances undergo change: they can be formed or decomposed, or can react with other substances.

Difficulties in learning chemistry are attributed mainly to its abstract, unobservable, particulate basis and to the need for agile transfer across the various levels of chemistry understanding (Johnstone, 2000; Gabel, Briner, & Haines, 1992; Coll & Treagust, 2003). Several researchers (Gabel & Sherwood, 1980; Garnett, Tobin, & Swingler, 1985) suggested using concrete models to help students visualize the particulate nature of matter. With the advent of computer graphics, CMM (Computerized Molecular Modeling) has become sustainable. Incorporating CMM into chemistry courses has been found to foster understanding of molecular 3D structure and spatial ability and to promote meaningful learning (Barnea & Dori, 1999; Dori & Barak, 2001; Donovan & Nakhleh, 2001).

RESEARCH QUESTION AND POPULATION

While integrating PBL in an IT-rich environment into undergraduate chemistry courses, we combined the PBL characteristics described by Krajcik et al. (1998), Marx et al. (1994), and Thomas (2000). Our PBL had a variation on the driving question, which originated

from the instructor rather than from the student and was conducted in an IT-rich environment. Additionally, the student autonomy element in our version of PBL was manifested as independent, individualized work after class.

The research question was: What is the effect of IT-enhanced PBL on students' achievements in general and on their ability to traverse the various chemistry understanding levels in particular?

This study was conducted at the Technion, Israel Institute of Technology. Since most of the students study toward science or engineering degrees, they are required to take a general chemistry course as freshmen or sophomore. This study investigated 215 students who participated in three general chemistry courses taught by the same instructor and several teaching assistants.

The distribution of the research population into experimental ($N = 95$) and control ($N = 120$) groups was not random. Rather, it was based on the students' preferences of carrying out the project. One reason for doing so was the course instructor's position, who maintained that enforcing a new teaching/learning method against individual students' preferences is not acceptable. The other reason was that educational research that involves human subjects must consider their will and opinions. Moreover, forcing university students to act against their own will might adversely affect their behavior and attitudes, and consequently jeopardize the research reliability and its external validity.

The experimental group students consisted of those students who elected to carry out the IT-based project. They were credited with 5 extra points (out of 100) toward their course's final grade (but were not included in the posttest and final examination scores, which were used for the quantitative analysis). The extra credit was assigned to encourage students to participate in the PBL assignments. This was introduced since only few students elected to participate in a pilot study conducted a year prior to this research, in which no extra points were offered.

The self-selected research groups and the extra credit might have posed a threat to the research validity. We therefore investigated the experimental and control students' university entry-level grades and administered a pretest for examining the comparability of the two research groups in terms of their prior knowledge and attitudes. Table 1 presents the research population, including the students' major fields of study and the number of students in each course and research group.

During the chemistry course, both experimental and control students were exposed, both in lectures and recitations, to examples of the spatial structure of molecules, their computerized models, and the use of CMM software packages.

The amount of time (number of hours) each research group invested to prepare their home assignments after class was an important concern. The project-based assignments

TABLE 1
The Research Population

Course	Students' Major Fields of Study	Research Group	*N*
Principles of Chemistry	Chemistry, molecular biochemistry, material engineering	Experimental	26
		Control	36
Chemistry 1b	Biomedical engineering, electrical engineering, agricultural engineering, computer science, biology	Experimental	46
		Control	66
Chemistry 1a	Space and aerodynamic engineering	Experimental	23
		Control	18

were done outside the classroom and were spread throughout the semester. Interviews with a sample of experimental and control students ($N = 31$) established that students of both groups spent on average about two hours a week practicing chemistry after class. Control students spent the time on traditional problem-solving assignments, while the experimental students spent some of this time also to work on their projects.

To establish the baseline of the two research groups, we compared the experimental and control students' university entry-level grades. These Stanford achievement test (SAT) and grade point average (GPA) equivalents are a combination of the students' high school matriculation examination scores and a battery of psychometric tests in mathematics, English, and Hebrew. On the basis of these indicators, we found no significant difference between the entry levels of the two research groups. We also compared these two groups in terms of their prior knowledge in chemistry, considering whether they took an elective chemistry course in high school or not. We found no significant difference between the two groups in prior knowledge in chemistry.

To further establish the equivalent baseline of the two self-selected research groups, another comparison of the students' prior knowledge and attitudes was carried out using a pretest. These results are presented in the Findings section of this paper.

RESEARCH SETTING AND METHODS

Chemistry courses have been an important component of the science and engineering curriculum at the Technion, Israel Institute of Technology. Freshmen chemistry courses are traditionally taught as a lecture course along with recitations and laboratories. As new learning approaches and technologies have evolved, few chemistry instructors faced the challenge of changing their teaching methods. While the general chemistry courses in our research still contained traditional lectures and recitations, they also included some new elements: 3D simulations of computerized molecular models were demonstrated in class, two tutorial sessions were devoted to practicing molecule construction with CMM packages (see Figure 1), and students were encouraged to participate in an IT-based home project.

The Project

PBL principles are derived from the constructivist perspective emphasizing active learning and higher order thinking skills (Barab & Luehmann, 2002). The IT-based project in
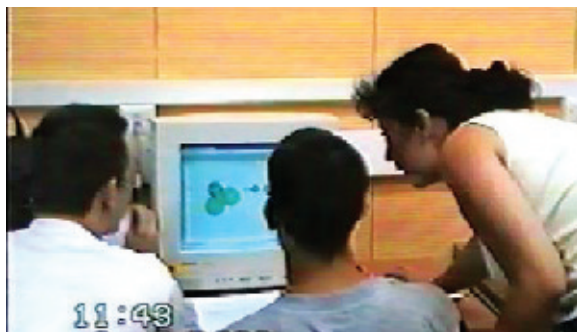

Figure 1. Students engaged in constructing computerized molecular models during recitation.

this research required using CMM packages to construct models of chemical compounds, solving real-life chemical problems, seeking information on the Web, exploring chemical concepts and theories, and presenting arguments. As part of the projects requirements, students used two CMM software packages they downloaded from the Internet. The ISIS-draw, MDL (2000), enables the construction of structural formulae. The WebLab Viewer, MSI (2000),[1] enables 3D visualization of molecules. ISIS-draw includes a toolbox that allows drawing carbon chains and rings, as well as single, double, and triple bonds. The software allows adding different atoms or complex functional groups and checking whether the constructed structural formula is correct. ISIS-draw enables the construction of structural formulae, i.e., two-dimensional structures. To view and inspect 3D models, students copied the structural formulae generated by ISIS-draw into WebLab. WebLab enables modeling and switching between three molecular representation forms: framework, ball-and-stick, and space-filling.

Since the project was carried out individually, each student received similar assignments with different chemical substances or theory to investigate. Four experts in chemistry and science education verified that the assignments were of similar difficulty level. The students' projects included three assignments titled *Molecules in daily life*, *Elements in the periodic table*, and *Scientific theories*. As part of the PBL approach, each assignment required an authentic investigation of the presented concept, the production of computerized models as the end products of the learning activity, and the use of a cognitive tool such as the Internet to support the process of inquiry.

The first assignment, *Molecules in daily life*, dealt with substances that are used on a daily basis, are found in humans and other organisms, have (or had) some application in daily life, or are of historical significance. These substances include Vitamins A, B, and C, urea, aspirin, nicotine, caffeine, adrenaline, citric acid, menthol, flavone, and tri-nitro glycerin (TNT). Using CMM software, each student constructed the structural formula of the molecule assigned to him/her and built 3D models in three representation modes: framework, ball-and-stick, and space-filling. Subsequently, the students had to compute the substances' molecular weight and indicate the hybridization and the electrical charge distribution for each of the carbon atoms in the molecule. In addition, the students had to respond to a real-life problem regarding the daily uses or applications of the substance.

The second assignment, *Elements in the periodic table*, dealt with identifying an element in a riddle, investigating the periodic table, and seeking information using the Web. An example of such a riddle is: *I can be found in batteries and colored old glasses, but not in pencils anymore, I am known for my high density and I am poisonous. Who am I?* [The answer: Lead (Pb)]. Students were asked to identify the element and present information regarding the date, place, and the way the element was discovered. They also had to present an image or visualization of the element, its chemical and physical properties, and its daily use or applications.

The third assignment, *Scientific theories*, dealt with the complex process of accepting or rejecting a theory. The students were asked to investigate the principles of a given theory and explain why it was accepted or rejected by the scientific community. In this assignment each student received a different theory. Some theories, such as cold fusion and poly-water, were rejected, while others, including molecular orbitals, quantum theory, acid–base by Lewis, and Schrödinger's atom model, are accepted.

Although the students investigated different chemical substances and theories individually, collaboration did occur spontaneously throughout the experiment. Computer-literate students helped their peers download the CMM programs, and students with better chemistry

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[1] WebLab Viewer was shareware at the time the experiment was conducted.

background helped others to solve chemistry problems. Moreover, at the end of the semester, students shared the knowledge they had acquired by uploading their projects to the course Web site for the benefit of all classmates.

In summary, this IT-rich project bears most of the PBL characteristics found in the literature. These include

- the centrality of the project topics in the general chemistry curriculum;
- the driving questions on which each project focused and with which students had to struggle in order to internalize central chemistry concepts and principles;
- investigations through which students constructed their own knowledge;
- realism and authenticity of the projects; and
- the use of IT-based cognitive tools to support inquiry.

Research Instruments

The effect of the PBL was examined both quantitatively and qualitatively. The quantitative analysis was based on a pretest, a posttest, and a final examination. The latter served for comparing the learning gains of the two research groups. The qualitative instruments, which were applied only to the experimental students, included projects' content analysis, "think aloud" interviews, and observations. The qualitative results helped us gain deeper understanding of the statistical results. They also enabled the characterization of the students' learning process while they were engaged in constructing 3D models as part of their PBL.

Pre- and Posttests. The pre- and posttests were administered at the first and last week of the 14-week semester, respectively. Both tests consisted of similar questions investigating similar thinking skills. The pretest examined the students' prior knowledge in chemistry and their attitudes towards project-based and Web-based learning. The posttest was designed to investigate the knowledge students gained and their attitudes. The pretest scores served as covariant for analyzing the posttest scores.

The first question in both the pre- and the posttests investigated the students' ability to traverse the symbolic, macroscopic, microscopic, and process levels of chemistry understanding (Figure 2).

The pretest question, presented in Figure 2, referred to three compounds: calcium carbonate, hydrazine, and hydrogen sulfide. Since very few students coped successfully with the calcium carbonate, we included it in the posttest as well, along with two different compounds: iron and glucose. The second question investigated the students' ability to apply transformation from one-dimensional molecular representation to 2D and 3D representations and vice versa. The first and second questions were developed and validated by Dori and Barak (2001), whereas the third question, which investigated students' reasoning ability, was developed and validated by Reid (1999). The second and third questions are presented and discussed in detail by Dori, Barak, and Adir (2003).

In the last section of both the pre- and posttests, we investigated students' attitudes toward Web-based and project-based learning. This section included 14 statements on a 1 to 5 Likert scale, with 1 being "strongly disagree" and 5, "strongly agree." Five experts in science education research established the pre-and posttests content validity. The Cronbach coefficient alpha for internal reliability for the attitude section was 0.84 for both the pre- and posttests.

Chemistry Course Final Examination. The final examination, which was written by the chemistry instructor, included open questions about the atomic theory, stoichiometry,

1a. Match each compound in the table below with its formula, properties and model from the given lists.

| Compound	Molecular formula	Properties	Model
Calcium carbonate			
Hydrazine			
Hydrogen sulfide			

List of formulae

1. H_2S 2. $CaCO_3$ 3. N_2H_4

List of Properties

- A colorless liquid, spontaneously ignited when comes in contact with Oxygen. Reacts strongly with oxidation agents. Its solution is used as fuel for jet airplanes and rockets.

- A white solid, found in marble rocks, lime-stones, and chalk. Serves as a substance for producing glass, plaster and cement.

- A colorless gas, very toxic, has an odor of spoiled eggs. It is Very common in swamps and hot springs.
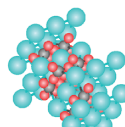
List of Models
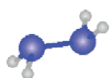
I   II   III

1b. Complete and balance the following chemical equations

$CaCO_3 + HCl_{(g)} \rightarrow CO_{2(g)} + \underline{\hspace{1cm}} + \underline{\hspace{1cm}}$

$N_2H_4 + N_2O_{4(g)} \rightarrow \underline{\hspace{1cm}} + N_{2(g)}$

$H_2S + 8SO_{2(g)} \rightarrow \underline{\hspace{1cm}} + S_{8(g)}$
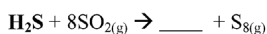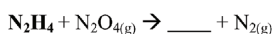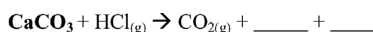
Figure 2. Question 1 of the pretest.

property of gases, liquids and solids, equilibrium, thermodynamics, kinetics, chemical structure and bonding, and molecular orbitals. Two chemical educators established the content validity of this examination. The reliability of the examination was based on the observation that its scores were consistent with those of prior semesters.

The university admission grades (SAT and GPA equivalents) were used as the covariant for the final examination to correct initial group differences that might have existed because the groups were self-selected. The university admission grades were used as covariate since they indicate the students' problem-solving abilities and science understanding.

Content Analysis of the Students' Projects. Content analysis of the students' projects was conducted and qualitative interpretations were constructed gradually. First, the students' answers to the inquiry-based questions were processed and analyzed, listing the words, concepts, and arguments they used. Second, categories were generated to determine meanings and relationships of concepts. Finally, text containing researchers' insights into the investigated students' projects was produced. Two experts in science education research were involved in the students' projects content analysis process. Both experts read

the projects, analyzed them, and discussed the results to establish the trustworthiness of the findings according to Denzin and Lincoln (2000).

Interviews and Observations. The interviews and observations helped us gain insight into the students' thought processes, based on Vygotsky (1978) description of language as a mediator of learning. Students' verbal expressions served for investigating their learning process and how they explain the notion of a molecule. About 25% of the experimental students ($N = 23$) were randomly selected for personal interviews and observations.

During the PBL, while the students were engaged in constructing virtual 3D models of their assigned molecule using the CMM programs, we observed and interviewed them. The students' drawings of the molecular formulae and the words they spoke out loud while doing so were audio-recorded and documented in the researchers' logs. Two science educators (the authors) analyzed the logs and audiotapes. On the basis of these findings we identified students' learning patterns with over 90% agreement between the two researchers.

Students often use various learning patterns when they engage in academic work. These include reading from a textbook, taking notes, studying for exams, and analyzing problems. As part of our investigation into the effect of the IT-rich project on students' chemistry understanding, we studied the patterns that students adopted while constructing computerized molecular models.

FINDINGS

The research findings are presented and discussed in four sections. First, we present the students' learning outcomes through statistical analysis of the posttests scores and the final examination grades. The second section presents statistical analysis of the students' ability to traverse the four levels of chemistry understanding. These two sections present quantitative results regarding both experimental and control groups.

The last two sections, which relate only to the experimental students, are qualitative in nature. They elucidate how students' participation in PBL affects their ability to traverse the four levels of chemistry understanding. The third section presents content analysis of the students' projects, whereas the fourth presents a case study of a student engaged in constructing computerized molecular models as part of the project.

Students' Learning Outcomes

Students' prior chemistry knowledge and their attitudes towards Web-based and project-based learning were examined at the beginning of the course through the pretest. The results are presented in Table 2. Analysis of variance showed no significant difference between the experimental and control group students in both variables.

TABLE 2
Students' Prior Knowledge and Attitudes

Investigated Variable	Research Group	*N*	Mean	SD
Knowledge of chemistry	Experimental	95	30.14	18.64
(on a 100-point scale)	Control	120	31.82	19.20
Attitudes towards Web- and	Experimental	95	3.87	0.84
project-based learning (on a 5-point Lykert scale; 5 is high)	Control	120	3.89	0.75

To investigate the effect of the PBL on students' achievements, analysis of covariance (ANCOVA) of the posttest and the course final examination scores was performed. Before choosing the covariate variables for the posttest and final examination, we investigated the relationships among the students' pretest, posttest, final examination, and admission grades using Pearson correlations. Because of a statistically significant correlation between the pretest and the posttest scores ($r = 0.38$, $p < 0.01$) and the students' university admission grades and the final examination ($r = 0.43$, $p < 0.01$), the pretest scores were chosen as the covariant for the posttest analysis, and the students' university admission grades were chosen as the covariant for the final examination analysis.

The analysis of covariance of the posttest and the final examination are presented in Table 3. That table shows that the experimental group students scored significantly higher in both the posttest and the course final examination.

To show the relation between the pretest and posttest scores, we constructed regression lines for each research group. These lines, shown in Figure 3, differ both in intercept and slope, indicating a growing gap between the experimental and control students. The regression lines can be used to predict the expected posttest score of a student given his/her pretest score and research group affiliations. For example, a student with a score of 20 (out of 100) at the pretest would score on average 50 in the posttest if assigned to the control group, and 70 if assigned to the experimental group.

Both Table 3 and Figure 3 show that the experimental group students, who participated in the PBL gained better chemistry understanding compared to their control group peers.

Students' Ability to Traverse Chemistry Understanding Levels

Students' ability to traverse the four levels of chemistry understanding—symbolic, macroscopic, microscopic, and process—was investigated by analyzing their answers to the first question on the posttest (see Figure 2). The question consisted of four parts, each relating to another chemistry understanding level: (1) recognizing the correct formula (symbolic level), (2) identifying the substances properties (macroscopic level), (3) identifying the correct model (microscopic level), and (4) completing and balancing chemical equations (process level). An ANCOVA test on the first question is presented in Table 4.

Table 4 shows that the experimental group students received significantly higher scores than their control group classmates in the question related to traversing the four chemistry understanding levels. Analyzing each one of the four question parts separately, we found that the significant difference in the overall score is due to a significant difference in the two parts relating to the two upper chemistry understanding levels: the micro level (identifying the correct model) and the process level (completing and balancing chemical equations).

TABLE 3
Analysis of Covariance of the Posttest and the Final Examination Scores

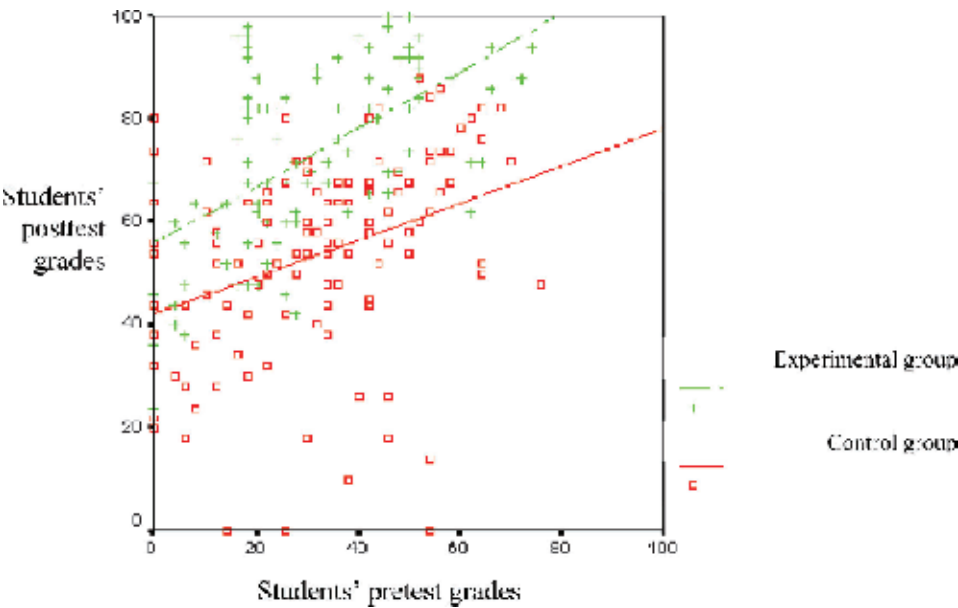| Dependent Variable	Research Group	*N*	Mean	SD	*F*	*p*
Posttest score	Experimental	95	72.7	17.6	57.49	<0.01
	Control	120	53.5	19.4		
Final exam score	Experimental	95	70.3	18.9	5.19	<0.02
	Control	120	62.0	25.2		

Figure 3. Regression lines showing the relation between the pretest and posttest scores.

Content Analysis of Student's Projects

To gain more insight on the above quantitative findings, we analyzed the students' project deliverables, which included, among other items, solutions to problems, images of 3D CMMs, and a list of references. In all, 95 project portfolios were submitted, and all were analyzed qualitatively. Following Denzin and Lincoln (2000), our qualitative interpretations were constructed gradually. First, the collected data was processed and analyzed by two

TABLE 4
ANCOVA of the First Question in the Posttest: Students' Ability to Traverse Chemistry Understanding Levels

Dependent Variable	Research Group	N	Mean[a]	SD	F	p
Students' ability to						
Recognize substances formula	Experimental	95	5.89	0.54	3.03	ns[b]
	Control	120	5.46	1.46		
Identify substances properties	Experimental	95	5.72	0.97	0.47	ns[b]
	Control	120	5.48	1.58		
Identify substances models	Experimental	95	4.99	1.70	40.70	<0.001
	Control	120	2.81	2.36		
Complete and balance chemical equations	Experimental	95	4.39	1.67	45.76	<0.001
	Control	120	2.27	1.97		
Question 1 total	Experimental	95	21.26	3.38	40.12	<0.001
	Control	120	16.28	5.28		

[a]The maximum grade for each part of the question was 6.00, and the maximum grade for the entire question was 24.00.
[b]ns: nonsignificant.

science educators. Categories were then generated, and finally, insight to the investigated phenomenon was produced and documented.

Findings show that students explored new concepts, examined and validated new information, and organized it to generate creative solutions to the problems and riddles with which they were presented. The vast majority (95%) of the references were URL links, implying that most students perceived the Web as an easy, accessible, and efficient source of information. Analysis of students' solutions revealed that while carrying out their assignments, students practiced transitions across levels of chemistry understanding and engaged in multidisciplinary learning. The examples of solutions to each section of the project presented below were taken from representative student project portfolios. The square brackets enclose the researchers' annotations on the levels of chemistry understanding and the multidisciplinary characteristics of the substances.

Section I: Molecules in Daily Life

> Vitamin C (ascorbic acid) is a water-soluble antioxidant and anti-scurvy drug commercially obtained from citrus fruits [macroscopic level; physical, chemical, biological, and medical aspects]. It is essential for the formation of collagen and aids in the absorption of iron [microscopic level; medical aspect]. Insufficient Vitamin C in the diet results in an inability to add hydroxyl (—OH) groups to growing collagen fibers, a task normally facilitated by this Vitamin [process and symbolic level; biochemical aspect]. . . . On Vasco da Gama's journey to the Cape of Good Hope, 1498, many crewmembers died from scurvy, a disease caused by lack of Vitamin C [Macroscopic level; historical aspect].

Section II: Elements in the Periodic Table

> The ancient Greeks and Romans used Alum in medicine as an astringent, and in dyeing processes [macroscopic level; historical, medical, and technological aspects]. Pure Aluminum is a silvery-white metal with many desirable characteristics: It is light, nontoxic in its metal form, nonmagnetic and non-sparkling [macroscopic level; physical, chemical, biological aspects]. Aluminum, $Al_{(s)}$, is an abundant element in the earth's crust, but it is not found free in nature [macroscopic and symbolic level; geological aspect]. The Bayer process is used to refine Aluminum from bauxite [process level; chemical industry aspect].

Section III: Scientific Theories

> The phlogiston theory is a hypothesis on combustion, which postulates that phlogiston is present in all flammable materials. Phlogiston is a substance without color, odor, taste, or weight that is given off in burning. The theory received strong and wide support throughout a large part of the 18th century, until it was refuted by the work of A.L. Lavoisier, who revealed the true nature of combustion [macroscopic and process levels; historical, physical, and chemical aspects].

> Lavoisier performed experiments that led to the modern understanding of the nature of combustion. Today, combustion, commonly called burning, is defined as a rapid chemical reaction of two or more substances accompanied by emission of heat and light. The burning of a fuel in oxygen, O_2, is a familiar example of combustion [process and symbolic levels; historical, physical, and chemical aspects].

The content analysis of the students' projects showed that while solving problems, students practiced traversing the four levels of chemistry understanding.

Constructing Molecular Models: A Case Study

We have shown that the information-seeking and problem-solving elements of PBL have had a positive effect on students' chemistry understanding and their ability to traverse the four levels. We now turn to examine the effect of another important element in chemistry PBL—the construction of computerized molecular models. In order to investigate the contribution of the 3D model construction on students' ability to traverse the levels of chemistry understanding, "think aloud" interviews and observations were carried out. Twenty-three students (about 25% of the experimental group) were observed and interviewed while constructing 3D models. While analyzing the data gathered using logbooks and audio-recording transcriptions, two characteristics of modeling became apparent. One is that the construction of 3D models fosters students to transfer across the levels of chemistry understanding. The other characteristic is that during the modeling process, students tread through a learning path that consists of up to five stages, culminating in a complete 3D model (see Table 5).

In order to demonstrate the pattern students followed while constructing computerized molecular models, we present the case study of Tammy, an experimental group student. Before Tammy started constructing the molecule she was assigned, the interviewer asked her to define the concept *molecule*. Her answer was, "Two atoms or more connected to each other." Tammy's partial definition was typical of that of other students' responses. Tammy was then presented with a drawing of the structural formula of flavone, $C_{15}H_{10}O_2$ (see Figure 4).

She was asked to explain her steps while constructing a computerized model of this molecule. As she started, she said, "I am going to draw atoms and then I'll connect them." Tammy used the "Atom" button on the screen to put C letter symbols of carbon atoms on the screen. Tammy then arranged the C symbols on the screen trying to form a hexagonal structure. With the help of the "Bond" button, she tried to connect the scattered carbon atom symbols. She chose to draw the structure formula from left to right. She found that it was difficult to place the symbols in such a way that they would form a perfect equilateral hexagon. Figure 5 shows Tammy's first step in attempting to build the flavone's computerized structural formula but failing to do so because of improper use of bonds.

Tammy then cleared the screen and tried again. In her second attempt, she typed both letters C and H [carbon and hydrogen atoms]. When asked to explain her actions, Tammy replied: "There are also hydrogen atoms. I think it would be better to add them too." Next, Tammy drew a single line and a double line [which represent covalent bonds] to connect the

TABLE 5
Five Stages of Constructing Computerized Molecular Models

| Student's Actions While Constructing a New Molecular Model	Researchers' Interpretations
1. Scattering letters and lines in an attempt to construct a cyclic structure	The student does not make proper use of chemical bonds
2. Trying to find an organized pattern for the carbon backbone of the molecular structure	The student attempts to understand the 2D molecular structure
3. Finding the carbon backbone of the molecular structure	The student understands the basic 2D molecular structure
4. Adding side chains and hydrogen atoms	The student fully understands the 2D molecular structure
5. Converting the 2D model into one or more available 3D representations spatial structure.	The student understands the molecule's spatial structure
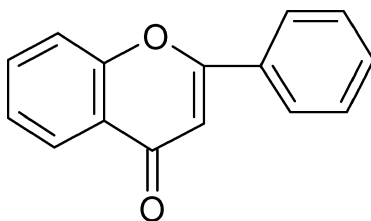
Figure 4. The flavone's structural formula from which Tammy was asked to construct the flavone's computerized model.

atom symbols, as shown in Figure 6. Tammy talked about the existence of double bonding, indicating that she was aware of different covalent bonds in the structure. At that stage she was trying to find an organized pattern for the molecule's backbone.

Pausing and looking at her second attempt of building the computerized flavone's structural formula, Tammy was unsatisfied.

Researcher: Why did you stop?

Tammy: I chose the wrong way to draw the molecule. I didn't succeed in connecting the atoms. Maybe there is another way... It looks very difficult... I don't know. [She shows signs of insecurity and despair]. This is the first time I am constructing such a complex molecule. In the tutorial sessions we built molecules, but simple ones... Maybe this project is not for me... I don't know...

Researcher: Tammy, try again.

Tammy: [Tammy looks at the structural formula for several seconds and says:] Rings, the formula consists of three different rings. [Tammy identifies the backbone of the rings and encourages herself out loud while constructing the computerized molecule's structural formula.]

Tammy was then at the third attempt to construct the computerized model, in which she succeeded in drawing the molecule's backbone and understood its pattern.

Tammy added the second hexagonal carbon ring that included oxygen atoms. She drew the external double bond with the help of the software tools, added the oxygen atom symbols,
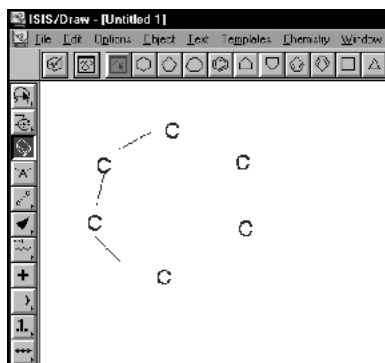

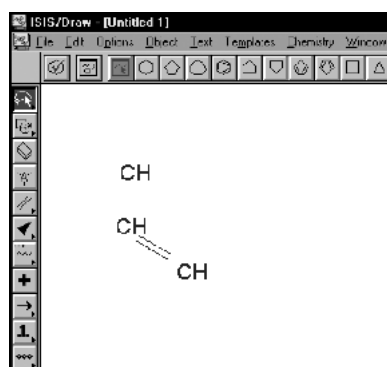**Figure 5.** Tammy's first attempt to construct the flavone's computerized structural formula.

Figure 6. Tammy's second attempt to build the flavone's computerized structural formula.

and started drawing the third hexagonal carbon ring by adding a single covalent bond (see Figure 7). Tammy's next step was to add the hydrogen atoms. She said, "Actually, it's easy. It's also better to see the molecule with the addition of hydrogen atoms . . . this way I can see the complete molecular structure." Figure 8 shows Tammy's final drawing of the computerized flavone's structural formula. At this fourth stage, Tammy fully understood the 2D molecular structure.

Tammy then exported the flavone's structural formula to the WebLab software, where she could convert the 2D structural formula into a 3D model. Tammy rotated the model and investigated it in three different representation modes: ball-and-stick, space-filling, and framework. At this fifth and final stage, Tammy chose the ball-and-stick representation (see Figure 9).

At the end of the 3D model construction process, Tammy was asked again to define a molecule.

> Researcher: Tammy, can you explain what a molecule is?
>
> Tammy: Well . . . [Tammy is rotating the flavone ball-and-stick model that is displayed on the computer screen] a molecule consists of different atoms connected through chemical bonds, it has a spatial structure . . . A molecule can also be defined as the substance's smallest unit that is typical to it [microscopic level of understanding].
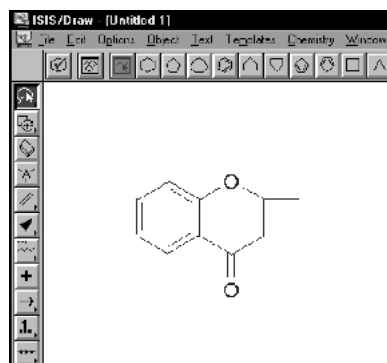

Figure 7. Tammy's work in progress—drawing the flavone's computerized structural backbone.
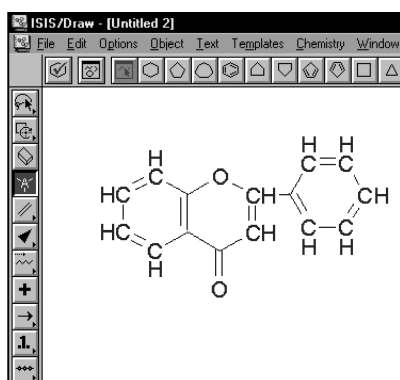
Figure 8. Tammy's final drawing of the flavone's computerized structural formula.

Researcher: What do you mean by "typical to it"?

Tammy: The molecular structure determines the substance property [macroscopic and microscopic level]. The functional groups determine its characteristics. Flavone has oxygen atoms that surely influence the properties of the substance [macroscopic and microscopic level].

Researcher: How?

Tammy: We learned that the oxygen is an atom with high electronegativity and high oxidation ability [microscopic and process level]. This has an influence on the substance boiling point, solubility, chemical reactions and more [macroscopic and process level].

Whereas Tammy's first definition of a molecule as "two atoms or more connected to each other" was simplistic and focused only on the microscopic level of chemistry understanding (atoms and bonds), her definition following the modeling experience was more sophisticated. It reflected her ability to make transitions between the symbolic, macroscopic, and microscopic levels, as well as to view a molecule as a spatial structure.
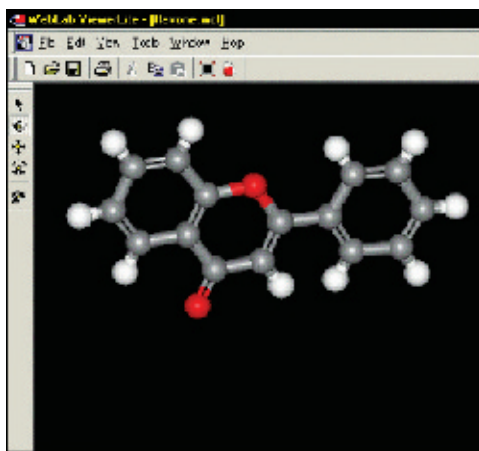

Figure 9. Flavone's ball-and-stick model as presented on the WebLab screen.

The five stages of constructing computerized molecular models were typical of most of the students. Some students, who had prior knowledge in chemistry, started the model construction process from the third stage of constructing the molecule's backbone. This was the case with Alon, another experimental student. Alon was asked to construct a computerized model of a nitroglycerin molecule, $C_3H_5N_3O_9$, from its structural formula. Prior to that, he was also asked to define molecule. His definition was as follows: "A molecule is two or more atoms that constitute the smallest component of a compound maintaining its chemical characteristics." This definition, though not perfect, reflects an initial higher conceptual understanding of *molecule* than that of Tammy. This is in line with the fact that Alon started right away at the third stage. He constructed the nitroglycerin molecule model by drawing a chain of three carbon symbols forming the molecule's carbon backbone. In the next (fourth) stage he added oxygen and nitrogen to complete the backbone and side chain, and finally he also added hydrogen atoms to complete the 2D structural formula. At the fifth and last stage, he converted the 2D molecular formula to a 3D model and investigated its spatial structure.

The construction of computerized molecular models helped students provide broad and complex definitions of the molecule concept. Students who constructed models with the help of visualization software realized that a molecule is not a random collection of atoms and bonds (letters and lines), but rather a 3D structure with chemical and physical properties. This qualitative finding, which was observed only for the experimental students (since only they carried out the project), was supported by the quantitative posttest results regarding both experimental and control students. As part of the second question of the posttest, the students were asked to define the molecule concept. Students who did not provide any definition or gave a wrong one did not score any points, those who gave a partial definition, such as "several atoms connected by chemical bonding," scored one point, and students who gave a broader explanation, such as "several atoms which are combined by sharing electrons to create a stable substance with minimum energy," scored two points. An ANOVA test proved that the experimental students (Mean = 1.13, SD = 0.71) wrote more elaborated definitions than the control group students (Mean = 0.63, SD = 0.63) and that the difference between the two research groups was significant ($F = 23.79$, $p < 0.001$).

SUMMARY AND DISCUSSION

Constructivist views of learning support construction of students' own knowledge through a process of interacting with objects and engaging in higher order thinking skills (Driver et al., 1994). Crawford (2000) suggested a model of instruction that involves the teacher modeling the work of scientists. In our research we went a step further and tried to give students a sense of what it means to be a chemist working in a computerized environment. The aim of the study was to investigate students' learning outcomes while they were engaged in PBL in undergraduate chemistry courses. The research outline is summarized in Figure 10.

The PBL presented in this study involved adopting new learning strategies and technologies. Implementing changes in the traditional way of teaching and learning in higher education is complicated, and so is the investigation of these changes. While studying the effect of the project-based approach on students' learning outcomes, we collaborated with the instructor of the three chemistry courses (Dori, Barak, and Adir, 2003). As noted, the instructor insisted upon giving the students the opportunity to elect whether they wanted to carry out the project. This implied self-selection of the research groups, which might have jeopardized the external validity of our research. However, the pretest we administered established the equivalence of the two research groups in terms of their prior knowledge and attitudes.
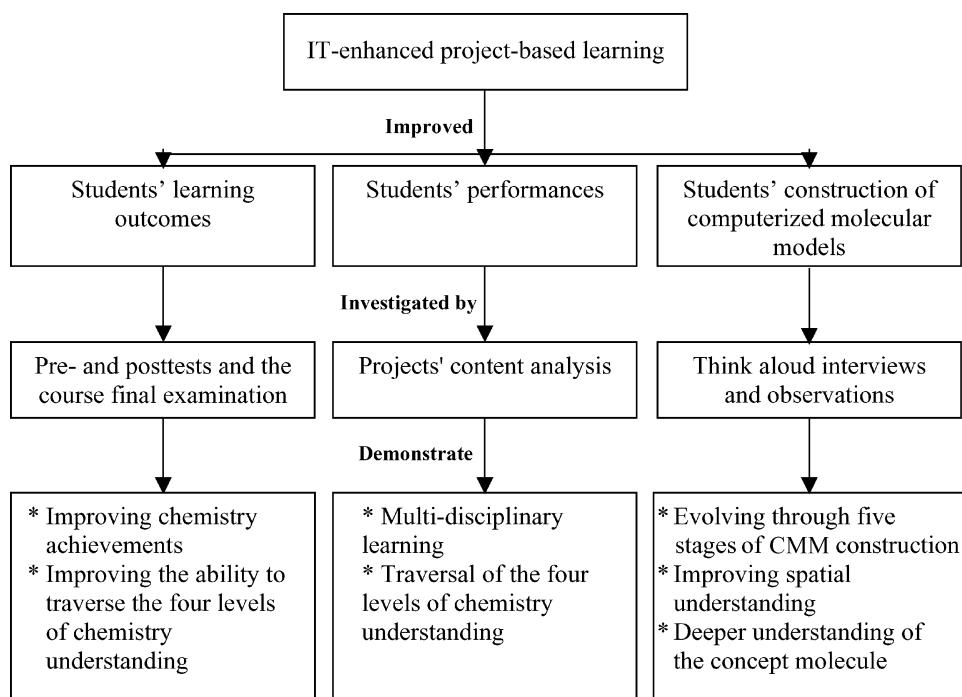
Figure 10. IT-enhanced project-based learning: research outline.

Our findings indicate that students who participated in the PBL performed significantly higher than their classmates not only on the posttest but also on the course final examination. Incorporating chemistry PBL into higher education enhanced students' understanding of chemical concepts, theories, and molecular representations. The construction of computerized models and Web-based inquiry activities promoted students' ability of mentally traversing the four levels of chemistry understanding: symbolic, macroscopic, microscopic, and process.

One of the theoretical contributions of this research is augmenting the growing body of knowledge on the use of CMM and visualization strategies in chemistry education. While the use of computers and information technologies in science education has become increasingly common, this by no means implies that technology is either well used or well understood (Mistler-Jackson & Songer, 2000). This study provided both qualitative and quantitative findings that show the positive learning outcomes of studying in a project-based approach that makes extensive use of CMM and the Web for visualization and information inquiry. These results are in line with the findings of other studies (Copolo & Hounshell, 1995; Donovan & Nakhleh, 2001; Harrison & Treagust, 2000; Kantardjieff, Hardinger, & Van Willis, 1999).

Another contribution pertains to understanding the effect of PBL on undergraduate students. Dori and Tal (2000) suggested that projects and task assignments should include elements of inquiry, argumentations, and authentic, everyday life context. Our study results show that projects that foster the combination of Web-based exploration of new concepts and theories, multidisciplinary learning, and practicing the traversal of the four levels of chemistry understanding, result in high achievements in undergraduate chemistry courses.

Bunce and Gabel (2002) claimed that "teaching the particulate nature of matter using two-dimensional pictures of atomic and molecular interactions to guide students to a visual understanding of chemical phenomena may be sufficient for detecting a difference in students' problem-solving ability" (p. 912). Our findings indicate that the use of static 2D or 3D representations of atoms or molecules alone may not be sufficient for students to develop understanding of chemical phenomena or enhance student's chemistry understanding. Both experimental and control students viewed drawings of 2D or 3D molecular models in their textbooks and class demonstrations carried out by the lecturer. However, the experimental group students, who actively constructed their own 3D models, gained better chemistry understanding (Dori, Barak, & Adir, 2003) and improved their ability to mentally traverse the four levels of chemistry understanding. Our findings are especially significant since Kozma (1999) found that chemistry experts frequently use several different kinds of representations to describe their scientific findings. What we have effectively done is mimicking for chemistry students the working environment of professional chemists.

Wu, Krajcik, and Soloway (2001) suggested that computerized models could serve as a vehicle for students to generate mental images. Our research results strengthen their claim and provide insight into the learning process with undergraduate students. We also found that students tread through a five-stage learning path of understanding and constructing 3D models of molecules. We suggest that these five operational stages correlate with the student's cognitive stages. At first the student views the molecule as a collection of letters [atoms] and lines [bonds]. At this stage, the student does not demonstrate understanding of the connection between the symbols and the chemistry behind them. At the second stage, the student attempts to create the molecule's backbone. At the third and fourth steps, the student gains understanding of the molecule's backbone and adds side chains and hydrogen atoms to complete the computerized model. The fifth and last stage of this cognitive and operative process results in understanding the molecule's spatial structure and improves the comprehension of the molecule concept.

Introducing PBL into higher education is likely to be met with reluctance or even opposition to adopt a variety of teaching strategies and technology-rich learning environments. Teachers have to customize their teaching styles and adapt to new contexts as well as students' needs (Polman, 2000). We recommend that the project-based approach be adopted in undergraduate science courses such that the innovative pedagogical and technological means match the scientific inclinations, budget, and personnel of the implementing institution. Further investigation of the project-based approach in other undergraduate science courses should be carried out to substantiate and strengthen our results.

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