Problem-Based Learning in Undergraduate Education

A Sophomore Chemistry Laboratory

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For the first time in my life what we were doing in lab had meaning to the outside world other than just mixing chemicals together.

— Comment turned in by a student in Chem. 291L

Problem-based learning (PBL) is a pedagogical approach based on recent advances in cognitive science research on human learning (1). A PBL classroom is organized around collaborative problem-solving activities that provide a context for learning and discovery. PBL has been used in medical schools to enhance the development of clinical reasoning skills and to promote the integration of basic biomedical sciences with clinical applications. Medical education literature is replete with articles on the practice and evaluation of PBL methods, but there is very little published on the application of PBL for science education in undergraduate settings. A recent paper by Dods in this journal describes a very interesting application of PBL in a biochemistry lecture course (2). There have been some presentations at recent ACS conferences describing the application of PBL in chemistry courses (3, 4). Other problem-based approaches to pedagogy have been described by Wenzel and Hughes (5, 6). These approaches are similar to PBL in that students learn in the context of an authentic problem solving experience.

This paper describes the implementation of PBL pedagogy in an undergraduate classroom setting. The author provides a brief description of PBL philosophy and PBL protocols, guidance on how to choose and design a PBL problem and integrate it into the curriculum, and a description of a laboratory course in which PBL has been successfully implemented.

What Is the PBL Process Like in the Classroom?

In a PBL classroom, students learn in the context of a problem to be solved. The responsibility for learning is with the students, not with the facilitator. There are five well-defined stages in the PBL process: introduction, inquiry, self-directed study, revisiting the hypotheses, and self-evaluation.

In the introduction stage, students are presented with a succinct problem statement that gives them a well-defined role that they can adopt. In the next stage, inquiry, the facilitator guides the inquiry process so that students elicit data about the problem, look for additional information in the materials provided (the inquiry materials), and write down the topics that they need to look up (the learning issues). The facilitator demonstrates how to organize the problem-solving process into distinct steps. The information generated in the discussion is entered in one of four categories: Facts, Hypotheses, Ideas, Learning Issues, and Action Plan. At the end of the first session, students commit to one of the many hypotheses and select learning issues that they will pursue independently.

Having committed to a hypothesis and chosen learning issues, students look up information from different sources—with some initial guidance—in the self-directed study stage. After their self-directed study, students evaluate the resources they used and share information with their colleagues during the revisiting the hypotheses stage. They reconsider their hypotheses with the benefit of the new information they have gathered as they try to solve the problem. Finally, during the self-evaluation stage, students are asked to evaluate their efforts and their groupmates’ efforts as problem solvers, as self-directed learners, and as members of a group and to discuss these evaluations with their group. During all these stages, the instructor facilitates the process by listening to the group’s discussion and probing their understanding, interceding appropriately when they proceed to apply their science knowledge (7, 8) and to model the problem-solving process.

PBL and Curriculum Design

It is important to ensure that the problem satisfies the curricular goals of the course and that the course fits within the curricular framework of the undergraduate program. Barrows suggests developing a curricular matrix to ensure that the curricular needs of a course are met in the problem chosen (7). The curricular matrix (Table 1) is a table of the problem components and the topics in the course syllabus and is illustrated for this course.

Designing a PBL Problem

In PBL classrooms, the choice of problem determines the probability of success of this pedagogy. The premise of PBL is this: if we give students a challenging task that engages them, they will learn to solve problems and they will acquire the associated knowledge in order to solve the particular problem at hand. Their learning will be deeper and more meaningful and will last longer, since it is knowledge that they have constructed themselves within a context and in response to a need (8, 9). However, this presupposes designing a task or a problem that will engage the entire class and also satisfy the curricular needs. The proponents of PBL, Barrows and Kelson, have developed a strategy for ensuring the success of the PBL process (10). Designing a problem involves choosing an authentic, real-world problem that students are able to see as genuine. PBL problems must (i) be based in compelling, real-world situations, (ii) generate multiple hypotheses, (iii) exercise problem-solving skills and require creative thinking, (iv) require knowledge and skills that satisfy curricular objectives, and (v) be integrated and contain components of more than one discipline.

Once a suitably compelling problem has been chosen,
it is important to bring the problem home to the students—to engage and excite them through the use of simulations, videos, newspaper or popular magazine articles, dramatization, and so on. It is also important that the students identify with the problem. The problem has to offer a clearly defined role for the students to adopt. The problem statement should also specify the deliverables. These project outcomes should be chosen with the class or curricular need in mind and should also appear to be a natural outcome of the problem itself.

PBL at Emory

The Integrated Labs are sophomore-level, 1- or 2-credit analytical chemistry labs that I teach using a PBL approach. Students have typically had one year of freshman organic and have placed out of general chemistry. Students work on the problem for a whole semester. In the 1-credit version described in this paper, they meet once a week for three hours. The lab time is used primarily for discussion and performing the experiments. However, we do spend some lab time training students to perform literature research and to use the instruments. In the 2-credit version of the course, students meet twice a week, with a one-hour discussion session and a three-hour lab session. It is during the lab session that students are trained and experiments are performed. The self-directed study is done entirely outside of the lab hours. Students are expected to spend two to four hours per week on the self-directed learning, including meeting as a group.

The Problem Statement: The Water We Drink

Atlanta has a serious problem with water quality; there is a federal ruling requiring Atlanta to reduce the levels of pollutants in the city's rivers. In fall 1996, students were "hired" by the Upper Chattahoochee RiverKeeper, an environmental advocacy group, to identify, understand, and run EPA-approved analysis on samples that they collected with the RiverKeeper's help. A member of the organization met with the students and discussed the problem with them. He explained that the RiverKeeper needed our students to run chemical analyses on water samples for them. He talked captivatingly to us and challenged us to do our best. He accompanied us on water sampling trips and demonstrated that the problem was authentic and really existed. We also collaborated with Georgia's Environmental Protection Division staff. After our students performed their water tests, we visited the Environmental Protection Division labs. Students then got an opportunity to see a real chemistry lab and also get some feedback on their data and techniques.

During the early lab sessions, students discussed what the RiverKeeper needed done. They generated multiple hypotheses of how to test for the different pollutants. They identified their learning issues and used a variety of learning resources for their self-directed study—Internet, library CD ROMs, textbooks, and other faculty. After self-directed learning, when students met in class, they were asked questions such as, "In your self-directed study did you come across anything that would help us rule out any of these ideas...?" Students would say, "Well, it turns out you can't really use NMR to determine phosphorus here because it would be too nonspecific" or "The EPA uses GC and UV–vis, but we don't have the detector they specify for the GC so I guess we could use the UV–vis method."

Students were required to post their findings on LearnLink, our campus-wide computer network. This provided both a means of communication and a way of documenting the interactions that took place.

In subsequent lab sessions, students brought different experimental protocols to the table. They discarded protocols that were not EPA protocols and experiments that could not be performed in our lab owing to nonavailability of equipment. Once the experiments were selected, the TAs helped the students to get the chemicals and equipment and trained them to use the instruments. Students then performed the experiments and analyzed the data and discussed the results.

We required that all protocols the students chose be EPA-

<table>
<thead>
<tr>
<th>Table 1. The Course Curriculum Matrix</th>
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<tbody>
<tr>
<td><strong>Syllabus Component</strong></td>
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<tr>
<td>Lab Techniques</td>
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<tr>
<td>Preparing solutions; dilutions</td>
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<td>Making up buffers</td>
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<td>Standardization</td>
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<td>Calibration</td>
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<tr>
<td>Distillation</td>
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<tr>
<td>Keeping a good notebook</td>
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Instrumentation and Analytical Methods

- Titration
- UV–vis spectrophotometry
- Gas chromatography
- Solvent extraction
- Electrochemistry
- Gravimetric analysis
- Infrared spectroscopy

**Note:** To illustrate the concept of a course curriculum matrix, this table shows the components of the Chem. 291L water quality problem.
approved protocols. Students mostly looked up these protocols in Standard Methods for the Examination of Water and Wastewater (11) or in an EPA Methods handbook (12). Some procedures were downloaded from the EPA database on the Internet. Some were provided by staff at the local state labs.

The class performed nine water quality tests in all. Each section of seven or eight students was divided into groups of two or three. Each group undertook the responsibility for one or two water quality protocols. Their duties included collecting the equipment for that protocol, running the standards, helping their classmates run this experiment, and finally collecting everyone's data and performing the data analysis. Every group had to perform all nine experiments at least once. Everyone was "trained" to run all the experiments. Before the sampling trip, each group was responsible for looking up the EPA recommendation for sampling water, shelf life of the sample, storage conditions, and recommended containers. When students were confident of their skills and ability to perform the analyses on the real water samples, we accompanied the RiverKeeper and collected water from a local creek. After the water was collected everyone had to run the experiment on the water. If class size, sample life, class time, and availability of equipment allowed, we were able to have more than one group perform the experiment.

Because students were following regular EPA protocols, not watered-down lab exercises, they had to deal with complex procedures and often unclear instructions in the sources they looked up. They also faced quality control issues for the first time in their lab. This made the experiments very real to them and also increased the time they spent in the labs. The experiments performed in the lab are summarized below. We focus on the relationship of the experiment to the topics in the syllabus. These pollutants were deemed important by the RiverKeeper. Details of the procedures can be obtained in the references.

**Nitrate** (EPA Method 353.3 [13]). Nitrate is important in freshwater samples for many reasons. Georgia waters have been known to have high nitrate levels. This experiment introduces UV–vis absorption spectroscopy.

**Ammonia** (EPA Method 351.2 [14]). One of our students lived close to a chicken farm that regularly violated the EPA standards for ammonia because of chicken blood in the water. Ammonia levels are regularly monitored by the RiverKeeper in North Georgia and students were therefore encouraged to learn about this test. We used a Kjeldahl as-say, involving distillation of treated water sample, nesslerization, and absorption spectrophotometry.

**Phosphorus** (EPA Method 365.1 [15]). Phosphate levels in the Upper Chattahoochee have been very important, since this is the pollutant that caused the unfavorable federal ruling in the first place. The City has responded by devising ways to lower phosphorus concentrations to acceptable levels. This is not an easy test to perform. It requires both time and practice and turned out to be the most frustrating test for the students. It is the third test that involves the use of absorption spectrophotometry.

**Oil and Grease** (EPA Method 1664 [16]). This test gave us an opportunity to reintroduce students to organic procedures such as gravimetry, distillation, and solvent extraction that they had encountered in the previous semesters. FTIR was used to obtain quantitative information.

**Volatile Organics** (EPA method 6231B [17]). This experiment introduced students to the quantitative use of capillary GC. This was a new procedure for most students and therefore interesting and challenging. We were able to detect hexachlorobenzene with the standards and column we used.

**Dissolved Oxygen and BOD** (EPA Method 213A [18]). The BOD test, biochemical oxygen demand, determines the relative oxygen demand of wastewater and streams. The amount of dissolved oxygen is tested at the time of sampling and after five days. The difference between the two readings gives us a chemical measure of the deoxygenating power of the water. This method involves the use of electrodes to measure dissolved oxygen and therefore provides us with an opportunity to discuss some electrochemistry.

**Hardness of Water** (EPA Method 130.2 [19]). Students learned to prepare buffers and standard EDTA and calcium chloride solutions. They performed standardization titrations and then repeated the titrations with sample water. This experiment gave students an opportunity to learn about buffers and to practice their titration skills.

**Fecal Coliforms** (20). The Georgia Environmental Protection Division analytical labs regularly perform bacteriological tests on hundreds of water sample every day. It was decided that this piece of information would be a useful indicator of sewage runoff—a persistent problem due to Atlanta's outdated sewage systems. The presence of coliform bacteria indicates that water has been contaminated with fecal matter, coming from sewage water and is therefore potentially hazardous to health. This experiment also gave us an opportunity to integrate biology topics into the curriculum. Students worked with the biology lab instructor to grow cultures. Statistical tables were used to quantify the observed results.

Table 1, the curricular matrix for the course, shows the breakdown of the syllabus and its coverage in the current problem. The curricular matrix is an important tool that helps determine and document the coverage of the syllabus. When designing the problem, the instructor lists the topics of the syllabus in the first column. As the problem is defined and developed, the instructor keeps track of the syllabus topics that the students are expected to encounter as they work on the problem. During the course of the semester if the students do not encounter these topics, the facilitator can guide them toward these topics. Students receive the list of syllabus topics so they know at the outset what they are responsible for, and this guides their self-study and choice of learning issues.

**Results**

We employed five measures (discussed below) to track students' progress and to evaluate the success or failure of the PBL methodology. We were interested in gathering evidence of increased student motivation and improvements in self directed learning. We asked the question, "Were there any changes in literature referenced—primary vs secondary, for example?" We looked for instances of knowledge acquired. We were also interested in documenting the depth of knowledge of skills acquired. Finally, we were looking for evidence of improving collaborative skills and group dynamics as the semester progressed.
Self-Study Logs

During the semester students maintained self-study logs where they kept track of which resources they used, the keywords they used in their searches, and the level of satisfaction they felt with each resource. We used these logs to see what kinds of resources students typically used in their self-directed learning and if these resources changed with time.

We noticed some changes in the use of reference materials. Most students started out using the Internet extensively. Early self-study logs are full of references to Yahoo and Excite, two common search engines on the Web. As the semester progressed, they looked more to textbooks and journals for in-depth information and they then rated the Internet sources lower on the satisfaction scale. We also noticed that as the semester progressed, they were more confident to discuss the problem with their previous lab instructors, the TAs, and other more experienced students.

Self-Evaluation Logs

Students also filled in self-evaluation logs, where they evaluated one another and themselves as problem solvers, as self-directed learners, and as members of the group. These logs were read aloud and discussed in the group sessions. We noticed a definite change in self-evaluations as the semester progressed. Initially, students were unwilling to say anything negative about anyone. Comments were uniformly complimentary and terse—"Good" was the most popular comment. However, after a few sessions where the facilitator modeled the process by evaluating everyone, including the facilitator, and students learned to trust one another, student comments became increasingly honest. Students improved their ability to evaluate themselves and their groupmates. They became more willing to bring up issues such as someone's nonperformance or habitual lateness and to admit if they received a great deal of help from one of their group members during the project.

One of the incidents that demonstrated students' confidence with the self-evaluation process was the way the group dealt with a certain self-confident person, X, who had excellent lab skills. The group told X that while they valued X's problem-solving skills and expertise in the lab, they found X to be patronizing and unwilling to teach others. They suggested that this student try not to do everything alone in the future but involve the rest of the group. This was a potentially explosive situation but the students handled it very well.

Students were also able to confront their own failings. One of the more irresponsible students habitually handed in material late. It was also clear to everyone that this person's self-directed study was superficial. Before the facilitator could bring this up in the evaluation sessions, this student commented that, as a self-directed learner, "I am a slacker who along with very little free time and personal family crisis had a hard time pushing myself. I wrote the lab reports and was ready for the labs but often did not thoroughly research learning issues. I promise to do better now."

We feel that the self-evaluation sessions helped students learn how to work in group situations, learn to evaluate themselves honestly and critically, and learn to give and take criticism constructively. These sessions also made students feel accountable to their group and their final goal.

Oral Presentation and Tour of Lab

Students give an oral presentation and a tour of the lab to the RiverKeeper and faculty in the department. This proved to be a powerful motivator. Students went to great lengths to become proficient in their experiments and to give a good presentation.

LearnLink Postings

Students' postings on a campus-wide electronic bulletin board, LearnLink, gave us another measure of the progress of the class. From students' messages posted on LearnLink, we obtained a record of student interactions that we could examine for evidence that students were learning the problem-solving process. Students posted messages not only to make meeting arrangements, but also to discuss the project, reflect on the process, share information with one another, and motivate one another. LearnLink provided us with a method to document the growth and development of our students as they learned to work in a group, feel a responsibility to the group, and work out interpersonal dynamics. We saw postings where students would apologize for failing their groupmates. We noted instances where students offered to help someone in the lab and where someone asked for help. Students showed a willingness to collaborate and share knowledge with the group and learned to deal with group problems in a constructive way.

1. Development of Responsibility. Students took on the responsibility of the problem and felt accountable to the third party involved (The RiverKeeper). This feeling of responsibility motivated them to spend long hours in the lab in order to get good data. They would post messages on LearnLink encouraging their groupmates to come into lab on weekends and during the Thanksgiving break so they could perform the experiments.

2. Development of Scientific Approach and Organizational Skills. Students displayed curiosity and took the initiative in solving the problem. They asked one another and faculty from other disciplines "what if" questions. They took the responsibility for organizing the experiment, for example, contacting the lab instructor of the organic labs for organic equipment. A lot of this organizing was done through LearnLink.

3. Development of a Group Feeling. Students learned to work in a group, feel a responsibility to the group, and work out interpersonal dynamics. We saw postings where students would apologize for failing their groupmates. We noted instances where students offered to help someone in the lab and where someone asked for help. Students showed a willingness to collaborate and share knowledge with the group and learned to deal with group problems in a constructive way.

4. Transfer of Knowledge. Students made connections to previous courses and made connections outside the project to real-world issues. They would make comments like "I know this because I just studied it in my physics course..." or "I didn't know this, but if you were a child and you drank water with so much nitrates in it, you would be pretty sick...".

Lab Evaluation

Students turned in a detailed anonymous lab evaluation at the end of the semester. Most comments on these evaluations were complimentary to the course. We noted that students found the problem relevant and enjoyable. Most enjoyed the...
group problem-solving process. Many felt that the problem was more meaningful than the usual lab exercises. On the negative side, they found the lab, especially the self-directed study portion, time consuming. This lab was run as a 1-credit course and students compared the time demands of this lab course with other 1-credit non-PBL labs where very little out-of-lab work was demanded of them. The lab will now be offered as a 2-credit course.

In addition to enhanced learning of chemistry related to the use of a challenging and worthwhile PBL exercise, other benefits of the method were discovered. Students realized with some surprise that they had in fact taken the responsibility for their own learning. “We had to look everything up.” “We had to take the initiative to teach ourselves or introduce ourselves to the subject matter.” “Making us find the information and do our research on our own definitely stimulated my self-directed learning.” “[I did the self-directed learning] or I would not have understood what was going on in discussion.”

Students learned about themselves as well as about the environment. “The course taught me not only chemistry but also a bit about environmental problems and about myself.” “It really gave me a chance to see a side of chemistry I never knew existed and to see that chemistry classes aren’t just a series of regenerating the information you’ve been told.” “It was challenging and worthwhile. For once a lab had a goal and not just a cycle to complete.” “Yes, I felt we not only enhanced our chemistry skills but also learned a bit more about groups fighting for the environment, the RiverKeeper.”

Conclusions

PBL has proven to be an effective way of motivating college sophomores. Undergraduates in a chemistry course at Emory worked on a problem of water quality assessment using the PBL methodology. If students are given an authentic problem that is challenging and real, they will be motivated to learn and to enjoy the learning process immensely. PBL problems can be structured to fill the curricular goals of undergraduate courses. When students follow the PBL methodology, they learn to gather facts specified in the problem, generate multiple hypotheses about how to solve the problem, identify topics that require new information, perform self-directed study in these topics, and evaluate their self-directed study and problem-solving skills. Student comments support the findings of cognitive science research that learning should be goal-driven and situated in a context (21).

Most exciting chemistry experience I have ever had! The goal-oriented structure of this course in which experiments were performed for a reason (i.e. steps to reach an ultimate goal) gave unprecedented interest to a chemistry course.

— Comments by student in fall ’96, Chem. 291L

Acknowledgments

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