A COGNITIVE MODEL OF PROBLEM-BASED LEARNING AND ITS APPLICATION TO EDUCATIONAL SOFTWARE DESIGN

Preetha Ram
Office for Undergraduate Education, Emory University
Atlanta, Georgia 30322, USA
pram@emory.edu

Ashwin Ram
College of Computing, Georgia Institute of Technology
Atlanta, Georgia 30332, USA
ashwin@cc.gatech.edu

Jennifer Holzman
Biology Department, Emory University
Atlanta, Georgia 30322, USA
jlholzm@learnlink.emory.edu

Chris Sprague
College of Computing, Georgia Institute of Technology
Atlanta, Georgia 30332, USA

ABSTRACT

Problem-based learning (PBL) is a constructivist pedagogy in which students learn in small groups by working on real-world problems. Despite its many benefits, however, this pedagogy is still not widely used in K-16 classrooms, especially with large numbers of students. Traditional human-facilitated PBL places intense demands on faculty to facilitate problem-solving sessions with small groups of students; on the other hand, most educational technologies do not provide PBL's collaborative problem-solving experience. We propose a cognitive model of the problem-based learning process. We present a software environment called CaseBook that allows instructors to author and share problems and provides students with a pedagogically-sound PBL experience based on the cognitive model. CaseBook has been used in high school and undergraduate chemistry and biology classes, and we discuss results from two studies in actual classrooms.

KEYWORDS

web-based problem based learning environment

1. INTRODUCTION: PROBLEM-BASED LEARNING

Problem-based learning (PBL) is a constructivist pedagogy that organizes curriculum and instruction around carefully crafted, ill-structured, real-world problems (Barrows, 1988). Guided by a facilitator, students learn content and develop critical thinking and collaboration skills as they analyze problems, formulate hypotheses, conduct searches, and formulate solutions in small groups. PBL enables students to embrace complexity, find relevance and joy in their learning, and enhance their capacity for creative and responsible real-world problem solving.

The efficacy of constructivist and inquiry-based approaches is well-documented in the field of science learning (Edelson, Gordin & Pea, 1999; Songer, 1996; Tabak & Reiser, 1999). Studies by educational psychologists and cognitive scientists have indicated that problem- and project-based learning centered around authentic problems are more likely to motivate students to think deeply about the domain being learned (e.g., Barrows, 1988; Ng, & Bereiter, 1991; Ram & Leake, 1995). In such approaches, students are required to take on the responsibility of learning. Such students also tend to be more motivated and to become better learners (Bereiter & Scardamalia, 1989). Involvement with the subject matter, as when students work on a challenging task, tends to hold student interest and ultimately leads to an increased retention of students in science. Problem solving is best learned when it is integrated with learning in a domain (Bransford et al, 1986; Brown et al, 1989; Ram, 1999). PBL specifically engages students in solving large complex, interdisciplinary problems while emphasizing the need for a deep, conceptual understanding. Such approaches are effective in learning both science content and skills (e.g., Barron et al, 1998; Kolodner et al, 2003; GCTV, 1998; Reiser et al, 2001).

Despite the many benefits of PBL pedagogies, however, PBL is still not widely used in K-16 classrooms (see K-12 URLs reference list for some recent projects in this area). One serious challenge faced by even expert practitioners of PBL is the intense demands this pedagogy places on faculty. It takes time and expertise to develop suitable problems, to coach students, and to facilitate problem-solving sessions. In larger classes, student-faculty ratios do not permit this level of individualized guidance.

Educational technology holds the promise of diminishing the burden on the instructor by streamlining the problem design and instructional processes. Web-based learning environments have the further advantage in that they can offer personalized learning tools to students of different abilities in and out of the classroom. However, to be effective, such environments need to go beyond electronic textbooks and autograded homework assignments, and provide students with a rich educational experience based on a sound instructional pedagogy. Unfortunately, most educational technologies do not provide the step-by-step problem-solving process or the small-group collaborative learning experience that are central to the PBL pedagogy.

We present a web-based learning environment based on PBL that offers the advantages of both the technology and the pedagogy. Designing such environments in a principled and repeatable manner requires us to develop a cognitive model of the PBL process and to embed that model into the learning experience provided by the environments. This point of this paper is to describe the cognitive model and the linear iterative strategy employed to teach students using technology-embedded PBL. Details of how the software is used by instructors are mentioned briefly, along with initial studies in a college chemistry class and two sections of a high school biology class. The results suggest that our approach is effective in providing the educational benefits of a traditional human-facilitated PBL classroom. Based on these results, we believe that this approach can increase adoption of problem-based learning in K-16 classrooms.

2. PBL COGNITIVE MODEL

PBL (and related inquiry-based pedagogies such as project-based learning, interactive case-based learning, and learning by design) are implemented in different ways by various practitioners, albeit with many similarities. To capture this pedagogy in a computer-based learning environment, one needs to (i) create a model of the step-by-step cognitive process that students are expected to follow, and (ii) implement this model in an environment that leads students through this process.

In our model, problems are structured as *Cases* with *Scenes*. The *Introduction* scene sets up the problem, one or more scenes introduce additional information as the “story” unfolds, and an *Epilogue* concludes with opportunity for reflective self-evaluation.

Students follow a three-step problem-solving process in each scene: *Analyze*, *Learn*, and *Reflect*. As students work on a problem using the PBL approach, they follow this process in a systematic manner on each scene.

Analyze

Students begin each scene by reading a *Scenario* and analyzing the information presented to them. They identify given information, or *Facts*, of the case. They generate *Ideas* and list hypotheses that may help them solve the problem. These are recorded in online group *Notebooks*.

Learn

Next, students identify learning *Issues* or areas of inadequacies in their knowledge that they need to address in order to verify their hypotheses or rule them out. These issues constitute their self-identified learning goals. They assign these issues to their group members and research them through a self-study process using *Resources* suggested by the instructor. After the self-study, students regroup to present their *Findings*, discuss and rerank their hypotheses, and generate new hypotheses and associated issues. This process continues until the students are comfortable moving ahead to the next stage.

Reflect

In the final step, students reflect on their group's answers as well as their approach to the problem. This step is facilitated through *Questions* posed by the instructor. Students develop and discuss their *Answers* to these questions. They also *Self-Evaluate* their approach to the problem.

A key challenge is to model the instructors' facilitation processes that provide scaffolding for the students' learning process. Since it is currently not feasible to automate human-level tutorial intervention, our model is limited to representing questions and comments the facilitator might provide as feedback. These may be provided as *Questions* in the Reflect stage, by annotating student *Notebooks*, or through discussions.

Three benefits are realized through this process. (i) Instructors can vary the degree of support and level of difficulty of a problem. (ii) Students are encouraged to reflect on their learning at a natural point in the process, a key aspect of the PBL pedagogy. (iii) Instructors can evaluate student learning for the purpose of providing feedback or the more mundane but necessary purpose of assigning grades.

This above process is repeated for each scene in the case. The Analyze-Learn-Reflect model is summarized in the following diagram.

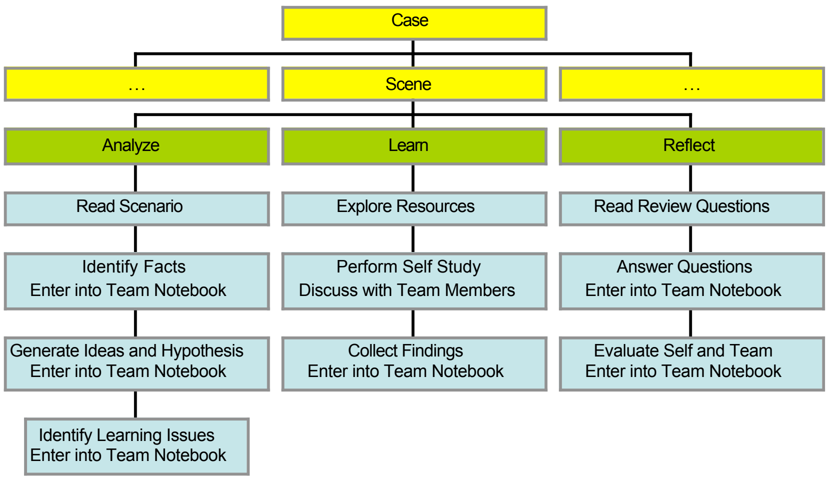

Figure 1. Analyze-Learn-Reflect.

Cases and Scenes

It is important to provide information about the case in successive stages (*Scenes* in our model). This restricts the amount of information available to students, allowing the case to unfold gradually. This approach has several benefits: it avoids overwhelming the students, it gives cases a natural "story-like" flavor, and it adds an element of mystery or game-like character which students enjoy.

3. THE CASEBOOK SYSTEM

Our team has been developing interactive computer systems incorporating the above model which (1) help teachers design, enter, and share problems, and (2) support students and guide them through the PBL inquiry process. To create such a system, it is essential to implement the PBL Cognitive Model as a step-by-step procedure. The sequential, iterative nature of the PBL process along with the Analyze-Learn-Reflect cycle are critical elements to the success of the pedagogy. Unlike a traditional cognitive model in Cognitive Science that executes algorithms corresponding to human thought processes, our systems do not execute this cycle as an algorithm but instead lead the users through it.

Our first environment, Virtual Sherlock, was used in a sophomore undergraduate analytical chemistry lab (Ram et al, 2000). While successful in some respects, it required a considerable amount of time and expertise to create each case and therefore was not scalable.

Our latest environment, CaseBook, expands the scope to enable PBL to be used by different educators in different classrooms. CaseBook makes it easy for educators to develop their own web-based PBL units without any special HTML or software expertise, share them with other educators, and use them in their classrooms. PBL units, called *cases*, reside in a searchable database and can be selected for use in the classroom. A user-friendly interface allows students to work collaboratively on the selected cases, with the system guiding them through the stages of the PBL process. The studies reported in this paper focus on the effectiveness of the learner's experience; in future work we will evaluate the reduction in educator workload. (Without the former there would not be any point to the latter.)

CaseBook is designed with four components. *CaseManager* allows teachers to choose the right cases for their class, manage the course and monitor student progress. *CaseExplorer* provides a problem-solving environment that guides students through the PBL process. *CaseMaker* guides teachers through the process of case development. Finally, the *CaseLibrary* serves as a central repository or database of cases.

Considerable engineering effort was required to design and develop all modules using professional, scalable best practices to ensure that the final "product" was usable by people other than those on our research team.

CaseExplorer

CaseExplorer guides students through the PBL inquiry process (see figure below). Cases are divided into scenes. Students work on each scene in the three-stage process suggested by the PBL Cognitive Model: Analyze, Learn, and Reflect. In the Analyze stage, students elicit data about the problem (Facts), generate ideas and hypotheses (Ideas), and identify questions and gaps in their knowledge (Issues). The Viewer shows the problem statement (Scenario). Group members share a Team Notebook, in which they record their Facts, Ideas and Issues via an online NotePad. At the end of the stage, they CheckIn their Notebook which automatically publishes their information for the teacher to view and provide feedback.

Figure 2. A screenshot of the CaseBook system.

In the Learn Stage, students seek to answer their Issues via self-directed learning. They look through teacher-provided Resources and access online textbooks or journals. The results of their self-study (Findings) are recorded in the Notebook using the NotePad and published via CheckIn for the teacher's feedback.

The final stage, crucial to true, sustainable learning, is called Reflect. Students answer Questions that probe their depth of understanding, and their Answers provide a quick rubric to assessing their progress. After this stage, students move on to the next scene in the case.

As students work through the scenes, they are always able to review their Notebook and view the Notebooks of other groups at the same level as themselves. Teachers can annotate the student Notebooks and provide feedback at any time. Students are encouraged to collaborate and discuss through an online chat room. At the end of the case, students perform a Self-Evaluation which is also recorded in their Notebook for teacher feedback.

Student-facilitator interactions are enabled in two ways. One is through the teacher's annotations or feedback and the the other is through the online bulletin board. Questions at the end of the case also help the teacher evaluate the progress of the students.

CaseMaker

A major benefit of the CaseBook architecture is the ease of development of new cases via a use-friendly web-based environment. Educators can create their own media-rich PBL units without needing a programmer or programming skills. Educators can share their problems, allowing other classes and educators to use the problems they've created and contributing to a growing database of problems. Moreover, just as the CaseExplorer leads students through the inquiry process and ultimately helps them learn the process, CaseMaker provides guidance on problem development and access to case analyses and case notes from other teachers to guide the choice of a case and its implementation in class. Teachers are immediately connected to a network of like-minded teachers in an online community.

CaseMaker provides several tools for creating cases. Cases can be divided into one or more scenes. This allows for flexibility in use, accommodating one-hour sessions, laboratory exercises, and multi-week projects. An easy-to-use Scenario Editor allows cases to be edited in a Microsoft Word-like manner without HTML knowledge. Documents, images, graphs, and URLs can be included to provide students with additional resources when they explore the problem. Educators may copy an existing case from the CaseLibrary and modify it to suit their own objectives.

The cases used in the studies described below were created using these tools; however, a rigorous evaluation of these tools is beyond the scope of this paper.

CaseManager

CaseManager includes administrative functions such as importing class rolls, organizing students into groups, and searching and selecting cases for a course from the CaseLibrary. It also lets the teacher monitor student Notebooks and discussions in the online chat room, and provides feedback via an online NotePad.

CaseLibrary

Completed cases on every topic are stored in the CaseLibrary, and are made available for use and modification by any instructor in any class. Modified cases are made available as a subsequent version, retaining the original version under the original author's name. Cases contain not only the scenes for students to work on but also the learning objectives and curriculum goals as well as suggestions for implementation, feedback from other instructors rating how well the case fit into their particular course, and statistics tracking how often a case has been used in a course. Cases often integrate learning objectives from different topics, helping students understand the material in a broader context rather then treating each topic in isolation.

A Sample Case (Abbreviated)

Digestive Distress *(A. Webb, J. Holzman & G. Louis)*
Level: 9th/10th grade Biology

Partial list of Learning Objectives

a. Students will define the following terms: pathogen, outbreak, parasite, food poisoning, sanitation, protist, protozoa, bacteria, virus.

b. The student will recognize normal and abnormal values for heart rate, body temperature, and blood pressure.
c. The students will distinguish between food allergies and illnesses caused by pathogens.

Scene 1
The Thursday after school starts...
Shelby and her college roommate, Twanda, head to Target after lunch to purchase the last of the items they need to finish decorating their dorm room. While deciding on matching comforters for their bed, Shelby suddenly feels very dizzy and has painful abdominal cramping.. She gets sick in the bathroom with bad watery diarrhea. "We gotta get home," says Shelby. "I'm really sick."

Stage 1: Analyze

Facts	Ideas	Learning Issues
Shelby and Twanda are roommates. They go to Target. Shelby has a stomach ache. She is sick in the bathroom. She has diarrhea. She is dizzy.	It may be her period. Maybe she ate something at lunch. Maybe she caught a bug. Maybe she is pregnant. Maybe Twanda has poisoned her.	Can periods cause diarrhea? How can we tell if it's a stomach bug? What are some food related illnesses? Dizziness and diarrhea—why? Did she travel? Is she having sex? What poison could cause these symptoms?

(These are some of the students' entries from their Team Notebooks.)

Stage 2: Learn

Resources
1. Google it! http://www.google.com/ 2. Wikipedia: The Free Encyclopedia, Diarrhea http://en.wikipedia.org/wiki/Diarrhea 3. National Digestive Diseases Information Clearinghouse (NDDIC) http://digestive.niddk.nih.gov/index.htm

(Students learn to post longer and more complete findings. Their Team Notebook becomes a record of their problem solving and learning processes.)

Stage 3: Reflect

Review Questions	Answers
1. What system of the body is involved in diarrhea? 2.What are causes of diarrhea?	1. Gastrotestinal Tract 2. Parasites, such as Cryptosporidium parvum, Cyclospora cayetanensis, Entamoeba histolytica,

(As the case progresses, review questions increase in complexity and student answers also get increasingly detailed as students learn to meet the teachers expectations. The resources are matched to student learning levels.)

4. EVALUATION AND RESULTS

We report on two different evaluation studies, one in a 50 student general chemistry college course and one in two sections of a 41 student high school biology class. Evaluation of PBL is always difficult. Regular testing protocols for large introductory courses are usually composed of multiple-choice questions. The skills learned in a PBL setting involve collaborative learning, looking for information from multiple sources (usually not allowed in closed-book college exams), forming hypotheses and solving complex multi-step problems.

In the first study, initial evaluation focused on the effectiveness of CaseBook-based learning compared with traditional lecture-and-textbook learning in a freshman-level general chemistry class at Emory University. We included three kinds of questions in the final exam: (1) traditional multiple-choice and short-answer questions based on lecture-and-textbook material, (2) multiple-choice and short-answer questions based on material students should have learned through self-study while working on a case, and (3) a complex, multi-step problem with a fair amount of irrelevant information. We also handed out a survey and collected their comments at the end of the course.

We measured the class average on questions of type 1 (81%), type 2 (82%), and type 3 (77%). This demonstrates that students were able to learn material not explicitly presented to them through the PBL self-study process at least as well as through a traditional presentation. They also did almost as well on the significantly more difficult multi-step problem. More experimentation is needed to unpack these results and measure retention over time.

The second study was performed at North Springs High School, a public school in the Atlanta metro area. Results from this study also suggest that CaseBook is effective. CaseBook was used in two sections of a 9th grade biology class, a remedial section (17 students) and an honors section (24 students), for a multi-day PBL-based curriculum unit developed by the regular teacher for that class. Each section was divided into two groups. One group used a traditional paper-and-human-facilitator approach. The other group worked on the same unit using CaseBook. Students worked on the case in small groups but were given individual pre- and post-tests to evaluate their learning (see Appendix B). The results indicate that CaseBook is an effective way to employ PBL methodology in the classroom:

Table 1. Evaluation of High School Casebook Users

	Traditional	**CaseBook**	**Average**
Pre-test	4.5	3.94	4.06
Post-test	4.5	5.44	4.97

The qualitative data are very interesting. Initial response to the first case was quite negative. Students needed a lot of help getting used the interface. We are working on these aspects of the system. Students questioned the relevance of the material they encountered in the case to the curricular objectives of the course (the familiar "Is this going to be on the final exam?" phenomenon). Students also needed to be encouraged to learn information on their own. They were too used to being told exactly what to learn, and found it initially unsettling to have to decide what to look up and where. Instructor feedback and guidance provided through the NoteBook annotation function available in CaseBook proved to be very helpful.

By the second case, most students were better able to handle the approach. The new self-selected groups helped reduce logistical issues of meeting times and schedules. The second case had some issue dealing with heroin abuse and physiology and our students really enjoyed that. By the third case, the quality of the postings had improved and the number of complaints had dropped significantly. Several students commented very favorably on PBL and were asking for a follow-up semester with PBL. Registration in another PBL-based course went up this semester with students commenting on their positive experience with PBL in our course.

Qualitative surveys indicated that students enjoyed working with CaseBook. As one student put it, "I'd even work with it at home." These results support our hypothesis that CaseBook is an effective way to use PBL-based pedagogies without the large amount of instructor time required by traditional PBL in classrooms with typical high school or college student-teacher ratios.

5. CONCLUSIONS

PBL can be modeled as a step-by-step cognitive process. This model can be embedded into a software environment that provides the benefits of PBL pedagogy without requiring a large amount of instructor resources. This paper describes CaseBook, a software system designed using these principles, and its use in undergraduate and high school science classrooms. CaseBook allows instructors to author and share cases, select and assign cases to their class, monitor progress of student groups on the assigned cases, and provide feedback to students as needed. CaseBook also allows students to work on cases in small groups, following the PBL learning process which is embedded in the design of the system.

Initial studies indicate that CaseBook is easy to use without specialized training and provides many of the benefits of a full-fledged human-facilitated PBL classroom. We believe this approach can increase adoption of problem-based learning in K-16 classrooms. We are planning additional studies on the effectiveness of the learner's PBL experience, as well as studies to evaluate the ease of authoring cases and facilitating PBL from the teacher's perspective.

We have also received interest in using CaseBook for professional development for teachers. We expect teachers trained with CaseBook will not only realize the educational benefits of PBL but be more able to adopt PBL in their own classrooms.

Finally, using software environments such as CaseBook, learners can have the opportunity for individualized instruction in a private setting but with a richer learning experience than a traditional distance learning course.

6. ACKNOWLEDGEMENTS

This work was supported in part by the PRISM project funded by NSF-GK-12 and by a grant from the Howard Hughes Medical foundation to Dr. Pat Marsteller. We recognize the support of Pat Marsteller, Judy Dennison (Fulton County Schools) and Gerda Loiuzi from North Springs High School. We also recognize the efforts of Juan Carlos Santamaria, Chris Simpkins, Nick Underwood, Alex Rudnick, Scott Appling, and Roshan Menon of Georgia Tech.

REFERENCES

Barron, B.J. et al. The Cognition and Technology Group at Vanderbilt (1998). Doing with understanding: Lessons from research on problem and project-based learning. *Journal of the Learning Sciences*, 8:271-265.

Barrows, H.S. 1988. *The Tutorial Process*. Springfield, Ill.: Southern Illinois University School of Medicine.

Bereiter, C., & Scardamalia, M. 1989. Intentional learning as a goal of instruction. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser*. Hillsdale, NJ: Erlbaum Associates.

Bransford, J. D. et al.1986. Teaching thinking and problem solving. *American Psychologist*, Vol 41, pp1078-1089.

Brown, J.S. et al. 1989. Situated cognition and the culture of learning. *Educational Researcher*, Vol 18 No. 1, pp 32-41.

Edelson, D.C. et al. 1999. Addressing the challenges of inquiry-based learning through technology and curriculum design. *Journal of the Learning Sciences*, Vol 8 No.3 &4. pp 391-450.

Gordon, P.R., et al. 2001. The use of problem-based learning with urban minority middle school students. *Educational Horizons*, Vol 79. Pp 171-175.

Kolodner, J. L et al. 2003. Problem-Based Learning Meets Case-Based Reasoning in the Middle-School Science Classroom: Putting a Learning-by-Design Curriculum into Practice. *Journal of the Learning Sciences*. Vol. 12.

Ng, E., & Bereiter, C. 1991. Three levels of goal orientation in learning. *Journal of the Learning Sciences*, Vol 1. No. 3 & 4, pp 243-271.

Ram, A. & Leake, D. 1995. Learning, goals, and learning goals. In A. Ram & D. Leake, (Eds.), *Goal-driven learning*, Chapter 1. Cambridge, MA: MIT Press.

Ram, P. 1999. Problem-based learning in undergraduate instruction: A sophomore chemistry laboratory. *Journal of Chemical Education*, Vol 76. pp1122-26.

Ram, P et. al. 2000. Virtual Sherlock: An intelligent computer-based PBL system, in *Proceedings of the 2000 PBL Conference*, Alabama.

Songer, N.B. 1996. Exploring Learning Opportunities in Coordinated Network-Enhanced Classrooms: A case of kids as global scientists. *Journal of the Learning Sciences* Vol. 5. No. 4, pp 297-327.

Tabak, I., & Reiser, B.J. 1999. *Steering the Course of Dialogue in Inquiry-Based Science Classrooms*. Presented at the Annual Meeting of the American Educational Research Association, Montreal, Canada.

dist.maricopa.edu/pbl/ubuystudent/index.html