Implementation of Problem-Based Learning into Engineering Thermodynamics

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Abstract

Problem-Based Learning (PBL) is an instructional pedagogy founded on the promises of knowledge construction by inquiry. Learning occurs by asking and obtaining answers for questions that are open-ended and challenging. This approach presents many challenges to students but capitalizes on having a real-life problem as the starting point. PBL is known for naturally combining classroom learning with real-life applications. This approach places the burden of knowledge acquisition on the students and utilizes the instructor as a facilitator. It is a student-centered approach emphasizing self-confidence and creativity. This paper presents the implementation of PBL curricular materials (modules) in Engineering Thermodynamics that are supported by technology through simulations and target higher levels of Bloom's Taxonomy of Learning. Undergraduate students go on to future courses with enhanced thinking skills and greater retention of knowledge. Thermodynamics is restructured as modules presenting practical applications first whereas principles are introduced just-in-time and as encountered. Theoretical information is presented to support the understanding of knowledge as students apply inquiry-based learning. These modules are carefully designed to reflect traditional concepts but made more exciting as students discover the need for the laws and principles. The paper documents steps and challenges in implementation and presents formative and summative assessment data for examining the effectiveness of the PBL approach.

Introduction

Problem-Based Learning (PBL) is teaching/learning approach which promotes critical thinking utilizing real-life problems as the starting point. The practicality and relevance of the problems serve as the motivation for solving them utilizing students as authentic investigators and the instructor as a facilitator. Uncovering fundamental principles and concepts occurs just in time as students plan, formulate, and solve the problem. Students are not left wondering if what they are studying has any use, but rather challenged by the excitement and relevancy of solving real-life problems. More than motivation exclusively, a problem-based approach helps develop independence in students, along with promoting creativity, critical thinking, and life-long learning.

Indeed, professors and students are expected to play non-conventional roles by engaging in this instructional and learning approach. In a PBL environment, learners practice higher order cognitive skills (analysis, synthesis and evaluation) and are constantly engaged in reflective thinking asking questions that are based on “why and how” rather than “where when, and what”.

PBL has been employed in a number of disciplines, particularly in the medical field[1 - 4] and in education-related professions.[5 - 9] Recent work, some with support from NSF, has targeted the fields of engineering and applied sciences in both course reform and complete curriculum reform.[10 - 14] In these sources, PBL was reported to help students' progression into the higher levels of Bloom’s Taxonomy of Learning with activities that are focused mainly on application, analysis, and synthesis; and to significantly improve problem analysis and solution, finding and evaluating resources, cooperative teamwork, and communication.

In an experiment on integrating problem-based instruction in an early Digital Systems course[15], it was noted that the problem-solving skills acquired in such a course were comparable to those normally associated with capstone courses. When PBL was introduced into a course on Vibrations[16], it was mentioned that the increased involvement of self-instruction caused students to spend more time working on this particular course. In a related application of just-in-time-learning and design-integrated instruction in a second course on Applied Thermodynamics[17], the authors found this approach to reinforce concepts and that their objectives were successfully met, despite a handful of students’ comments citing an overwhelming workload. In a capstone design course in environmental engineering focusing on simulation and a PBL design project, the authors reported that students developed a much deeper understanding of course material, suggesting that the simulation activities outperformed their expectations.[18]

At MIT, PBL has been implemented through a curriculum change based on the real-world engineering context of a product's complete life cycle. Students reported on the program being more interesting, having a better learning environment and noted that they gained a higher understanding of engineering science.[19] Using PBL in a Mechanics of Materials course, the authors noticed a growth in the “breadth and depth” of the students’ familiarity and understanding of the subject material.[20] When PBL was applied to a project course on calculators design, the authors reported that students developed significant skills in self-directed learning and enhanced their learning capabilities through cooperative learning.[21] Finally, in a white paper on future thermal science education, the authors state that "perhaps the most commonly used approach for development in the higher-level domains is problem-based learning ….. Technology can be a powerful partner to assist students in developing in higher order domains".[22]

This paper draws on the lessons learned in adapting and developing PBL curricular materials and documents its implementation into a first course on Engineering Thermodynamics, supported by simulations, and coupled with Bloom's Taxonomy of Learning. The driving motivation is to help students avoid memorization, to free them from being equations-driven and "pluggers and chuggers", and to assist them in internalizing knowledge and understanding through critical thinking. Effectiveness of using this instructional approach is evaluated for the purpose of examining its effect on students’ learning.

Modules Description: Approach and Guidelines for Implementation

The curricular materials developed here are based on lessons learned from the PBL literature, guided by field-tested characteristics. The guidelines are as follows: (1) Students would benefit from an orientation program which describes this instructional method, the role of fellow students and the facilitator, and the expectations; (2) the design of appropriate PBL problems is key to its success; (3) features of a good problem involve familiarity, relevance, dramatic appeal, significance, authenticity, and group collaboration; and (4) the design and use of appropriate assessment methods. Therefore, the first lecture is dedicated to talking about traditional methods of teaching engineering and engineering science courses as compared to PBL. Students get exposed to a series of complex problems (applications) with the intent of allowing them to be prepared for a different operational plan where they are being called upon to handle a substantial part of the learning process. The design of PBL problems should ensure, at a minimum, achievement of stated outcomes. These problems are designed to capture traditional course coverage and allow for the adaptation of PBL characteristics and generate an interest in self-directed learning. The course culminates in an open-ended design-type experience where students apply the laws and principles they have learned to an energy conversion application. Students submit a formal report on their project at the end of the term. The project emphasizes self-learning, cooperative work, team-work, and communication skills.

A general skeleton of the module-structured Problem-Based Engineering Thermodynamics (PBET) is made up of basically five modules and has been described at length in an earlier publication.[23] The five modules are: (1) Spark/Compression Ignition Engines, (2) Steam Power Plants, (3) Power Gas Turbines, (4) Vapor Compression Refrigeration, and (5) Transient Problems. A common list of educational objectives and related outcomes for the course was established. This list is based on consultation with other faculty members who teach this particular topic and are consistent with what is taught nationally. Course Learning Outcomes are mapped to the modules and thus students are expected to achieve these outcomes by going through modules' contents and related topics. These educational outcomes are made known to students and after each module are brought back into the picture for discussion and reflection on extent of achievement. In addition, assessment via examinations of students' knowledge and skills is carried out in a way that is consistent with these educational outcomes.

Earlier results of a pilot study have been encouraging and have also appeared recently.[24] The module-based layout does not compromise typical topical coverage[25] but rather encompasses coverage in the context of real-life, open-ended problems. For each module, students tackle a practical, complex but well-designed, problem(s) to solve, employing just-in-time discovery of principles in a cooperative-learning environment. The class motto is "think better and retain more". The first two modules are, to a large extent, the largest and most extensive as concepts encountered there are extended to the other modules. The instructor first introduces the application, followed by the students setting initial desired objectives (power and efficiency) of the problem. The instructor facilitates the modeling phase, probing students on their knowledge of engines. Students break into 3-4 person teams for five-minute brainstorming sessions, task formulation, and direction identification. Through an interactive discussion, students experience an online simulation on the operation of an automotive piston-cylinder as an engine demonstrator, assisting students in visualizing processes in a real engine. Students then describe the processes among themselves, leading up to the need for and discovery of an energy principle, and queuing the instructor to formally introduce the 1st law. Students move into the 2nd law domain, challenged by the instructor to raise the efficiency. Here, reversibility and irreversibility are introduced along with the 2nd law, isentropic relations and entropy generation. The first module concludes with a problem on Compression Ignition (CI) engines where concepts seen and utilized earlier are reconfirmed and "enthalpy" is encountered and introduced. Thus for the CI problem, the process begins anew but in a rapid manner, building on the material and concepts learned from the SI portion. Students identify differences and similarities to SI engines and related processes. Cooperative teams are again employed to apply the learned principles and confirm their understanding of the 1st and 2nd laws. A substantial part of learning and thinking is shifted onto students' shoulders since the instructor facilitates learning and presents principles as needed.

The second module treats steam power plants and makes the jump from control mass (closed systems) to control volume (open systems). Students begin with an online tour of a coal-fueled steam power plant, detailing the function of each component. The challenge lies in handling pure compressible substances and the fact that the ideal gas law does not apply to water. Students are asked to examine what happens to water as it becomes steam and identify the need for properties of a pure compressible substance, distinctly different from ideal gases. Students identify components of the plant and determine needs and objectives, discovering that the 1st law for a closed system requires modification to be used for open systems, and seeing the concept of "flow work" for the first time. In improving thermal efficiency, students relate to the need for the isentropic efficiencies of devices. The instructor facilitates coverage of issues, concepts and topics based on students' needs and time constraints for the course. Each of modules 1 and 2 consumes four weeks of instruction.

In the third module, students tackle gas turbines whose components are open systems and substance an ideal gas. Having seen all needed fundamental principles, students revisit the ideal gas model and feel more comfortable applying the 1st and 2nd laws for open systems. Students develop their objectives (power-efficiency-thrust) and exhibit their problem-solving skills. In addition to the fact that the application is exciting (producing power, turbo-jets, turbo-props), this module boosts students' confidence in their abilities to think critically and independently. In-class instruction time for this module is a two-hour block only.

In the fourth module, students realize also that this application is based on previously seen governing principles (1st and 2nd laws) and cruise through the solution to such problems. Students practice more critical thinking skills, feel at ease dealing with compressible substances (refrigerants), and encounter coefficient of performance as a measure of systems' efficiency. Students revisit Carnot principles, realize Clausius statement, and examine ways to increase the COP. Students spend less than a week on this module. The open system modules addressed steady-state, steady-flow devices and therefore a different type of a problem is needed for unsteady situations. Therefore, in the fifth module students solve a small problem of charging an empty tank and rewrite/apply the first law of thermodynamics.

Classroom Environment:

The classroom environment is based on the philosophy of "guided discovery". Thermodynamics is taught in blocks of two hours of instructional time, ideally suited for open-ended problems. The ambience is rather informal, cooperative and non-threatening. After each individual lecture and as students solve more aspects of the problem, each individually generates a Concept Table. Such a table features a layout of thermodynamic concepts (terms), what they mean to the student (in his/her own words), and any supporting equations. At the end of each module, students build on their Concept Tables by generating (in groups) Concept Maps. The purpose of this map is to develop critical thinking skills and help students become concepts-driven as opposed to being equations or "formulae"-driven. Also, students are asked to construct a Reference Table, cross-referencing discovered knowledge with sections in their own textbook.[25] This table is especially helpful to students as they link their understanding to textbook treatments and get another perspective on thermodynamic concepts. Towards the middle of the term, students go on a field trip to a power generation plant as this might be their first face-to-face interaction with real devices and systems. This course makes use of technology utilizing a dedicated site on the e-learning platform, Blackboard. Students have access to a number of resources. A useful resource made available at the conclusion of each module are files containing slides (ppt slides) of the concepts that are tied to that particular problem. The concepts are presented concisely and clearly, leaving no ambiguity on what they mean and how they should be applied. Additionally, the course is assigned a homework grader and he/she summarizes points that need to be re-emphasized or revisited by the student and the instructor as well to make sure problem areas are corrected. The BB on-line tool helps in communicating with students the grader's reflections and serves as an on-line trace to all such observations. Students expressed sincere appreciation for having the grader's comments and have used them to correct errors they have had with their initial solutions to the homework problems.

Simulations/Animations: Why and How?

Many students have not seen the devices, dealt with in Thermodynamics, in real-life and would benefit from just-in-time viewing of internal happenings of these devices. Intuitively, the use of a rich interactive multimedia presentation can be very effective for educational purposes. It enhances the understanding of complicated systems and theoretical concepts. One of the challenges in teaching thermodynamics is to relate physical concepts to mathematical terms. Both experiments and theory are useful in helping students make that connection. In recent years, computational tools have become more accepted as an adjunct to physical experimentation in the understanding of complicated engineering systems. However, computational tools have not yet been used significantly to have an impact on the teaching of thermodynamics. A common hurdle is the time needed to develop and test software for thermodynamic devices' simulation. This prevents their use for student projects and homework, and discourages instructors who do not have expertise in computer simulation software from using them.

The computer simulations/animations generated for this project are directly linked to thermodynamic principles and to the educational modules being developed. The simulations are to be used for just-in-time demonstrations as multimedia animations. With the use of these animations and presentations, fluid flow phenomena and thermodynamic processes that occur in complicated engineering systems could be demonstrated and explained using a virtual laboratory. Students would benefit from having these presentations available to them to view and review without having to be in a laboratory, or to repeat an experiment. In addition, modules will be incorporated into these presentations that would require students to interactively perform homework assignments and to test their knowledge in thermodynamics. It is anticipated that these presentations will help make thermodynamics more relevant and vibrant. Students are expected to gain a better understanding of thermodynamics and to develop a deeper appreciation of thermodynamic principles and their use in analyzing complicated systems. The simulations will also expose students to new state-of-the-art software and technologies. A course devoid of visual aids and computer technology is considered "low tech" to today's students. Moreover, it is very difficult to many schools to keep up with the rapid evolvement of technology that requires the acquisition of very expensive laboratory equipment. Computer software that could be constantly upgraded and provide simulations/animations, offer an attractive alternative to expensive experimentation.

Development of these animations relies on the use of commercial software packages like Star-CD and FIRE for CFD, and Macromedia Flash software for multimedia presentation. Macromedia Flash has advanced capabilities in creating a rich multimedia presentation. These presentations are integrated into the course in two ways. One way is to show some of these presentations during the lecture to aid the instructor in explaining some of the difficult concepts. For example, the Otto and Diesel cycles are the ideal cycles for the spark-ignition (SI) and compression-ignition (CI) engines, respectively. The combustion process in the Otto cycle is replaced by a constant-volume heat addition process, and by a constant-pressure heat addition process in the Diesel cycle. The simulations will be used to generate a PV-diagram of an actual cycle that will be used to explain why the combustion process is described differently in the two cycles. Another way is to make these presentations available to students outside the classroom by posting them on a designated website for the course, and by copying them on CDs. Some of these presentations will also be used as homework assignments. Students will be asked to view the presentation that shows the difference between the combustion process in an SI and CI engines and to explain in their own words the reason for describing it differently in the Otto and Diesel cycles. For completeness, additional simulations and animations in turbo-machinery and other flow devices are being developed. First –time deployment of these simulations/animations is the winter term, 2005.

Assessment, Evaluation, and Mastering of Disciplinary Knowledge:

In a paper on describing common characteristics of PBL, the authors emphasized the compatibility between the assessment method and the objectives of the learning process.[26] In addition, there are a number of sources that focus on assessment tools and techniques[27] but the literature lacks on assessment tools that are compatible with the PBL instructional method.[28]

Therefore, in order to ensure that desired outcomes are being measured, a number of assessment tools are used to evaluate the impact of PBL on students' learning, problem-solving skills acquisition, and critical thinking skills. The tools, discussed in an earlier paper, are as follows:

1. Professor's examination of students' homework assignments, and mid-term exams
2. Professor's examination of students' concept maps
3. Team project
4. Senior student observer diary
5. PBL-focused questionnaire
6. Common final exam for PBL-instructed students and traditional Subject-Based Learning (SBL) students
7. Simulations/Animations Evaluation.

Granted that characteristics of PBL are important, but for a course like thermodynamics, mastering disciplinary knowledge "takes a front seat". The issue of understanding disciplinary knowledge as tied to PBL was addressed recently.[29] The author recommends that instructors use strategies that engage students in revising existing knowledge and applying disciplinary concepts in multiple contexts. He also noted that students learn without understanding via a memorization process, accumulating material without achieving a grasp of it and students' preconceived ideas and beliefs about a subject interfere with new learning. This observation was experienced in Thermodynamics as students hurry to generalize the application of the ideal gas law to all substances and as they tend to substitute an adiabatic process for an isothermal process. Another example on developing misconceptions as they learn new material is illustrated by anticipating entropy change to be always positive confusing that with entropy generation. The author further points out that in the case of mastering specific concepts, the instructor should be explicit about the knowledge domain that is relevant to the problem. "Students are more likely to transfer knowledge if they understand it well, use it in multiple contexts, and become aware of how and when the knowledge applies to new circumstances."[29] The large problem in class, the module, targets the issue of initial grasp of the material, while the homework problems demonstrate using it in multiple contexts with the goal of encompassing the key concepts and ideas. Also, to help students internalize information and be self-conscious about their learning, students generate concept maps linking concepts to each other and applying them to new contexts. From our experience with the implementation of PBL in Thermodynamics, PBL has the potential for overcoming above stated obstacles so that students experience deep understanding and master the use of important concepts.

Results and Discussion:

As stated earlier and at the end of the term, students are asked to rate the contribution of this instructional/learning approach in providing them with certain desired abilities. These abilities ranged from Bloom's Taxonomy of Learning levels to enhancing their creativity and technical maturity. Results are summarized and plotted for both the Fall 2003 and Winter 2004 terms in Figures 1 and 2. Students reported high agreement with having acquired desired abilities in application, analysis, and technical maturity. They also believe that the teaching/learning environment allowed them to "think better & retain more". With respect to

PBL's features, students agreed that the approach is student-centered, that the material is relevant, that it combines classroom with real-life applications, and that it supports a climate of active engagement. As an overall indicator of the contribution level of the course in helping students acquire desired abilities, a rating factor was computed as follows:

$$\text{Rating Factor} = (4 * \text{High}) + (3 * \text{Above Avg.}) + (2 * \text{Avg.}) + (1 * \text{Minimum})$$

The rating factors for these PBL-instructed students are high and especially in some areas that are very hard to measure through students' work. Figure 3 displays these rating factors. These results are consistent with earlier results and show that students are quite receptive to the PBL instructional approach. As a final question on the questionnaire, students were asked to select their level of agreement in preferring the PBL approach to instruction over the traditional approach. The results are featured in Figure 4. Overall, 73% of the students seem to prefer the PBL environment over the traditional environment.

Another measure of the effect of PBL on students' learning is students' performance on a common final exam with Subject-Based Learning (SBL) students. The SBL students are taught in a traditional approach following the textbook sequence and going through the material, subject by subject, topic by topic, as they appear in a traditional textbook. The exam is designed to have twenty questions. These questions are tied directly to educational outcomes previously agreed upon by all instructors of thermodynamics. Figure 5 exhibits, on a question by question basis, the difference in students' performances on the final exam. Gathered data indicated that PBL-instructed students outperformed their classmates who were taught in a traditional way (SBL-instructed students). This is also consistent with earlier findings when the same comparison was done on another set of students in previous terms.

Challenges

There are a number of challenges that need to be overcome so that implementation is successful. These challenges are especially important for a course such as Engineering Thermodynamics where disciplinary knowledge forms its foundation. The following constitutes a list:

(1) Instructors need to constantly work on freeing students from being formulae-driven
(2) Instructors need to create a climate founded on understanding and synthesis rather than memorization
(3) Students need to adjust to solving real problems versus small homework problems
(4) Students need to practice further in sorting through information from multiple sources and in becoming organized
(5) Self-seeking knowledge/concepts, along with homework, is frustrating to students
(6) Working in groups presents a challenge to students
(7) Authenticity and open-ended nature of the problems maybe overwhelming to some students
(8) Assessment: When PBL assessment is done it is recommended that one use the following methods: (1) ability to reason through given information and identify a

solution approach to the problem, (2) ability to solve an unseen problem, and (3) based on a brief project statement, students apply team-based skills to produce a solution to a project idea, and (4) produce a formal report detailing their thought processes and documenting their solution to the project

(9) The instructor must keep a watchful eye on the balance between theory and practice Fundamental theories must not be overshadowed by the relevancy of the problems

(10) Animations/Simulations require a substantial time to develop and use effectively.

Conclusions

This paper presented developmental steps, challenges and results on the implementation of Problem-Based Learning in the form of guided discovery for a first course on Engineering Thermodynamics. PBL seems promising in providing students with desired abilities and capitalizes on its features. Although many challenges remain for smooth implementation, PBL seems to be well received by students. Comparison of students' performances on a common final exam between PBL and SBL students further supports the value-added of this teaching/learning approach. Qualitative and quantitative results serve as good indicators of the benefits generated from this approach.

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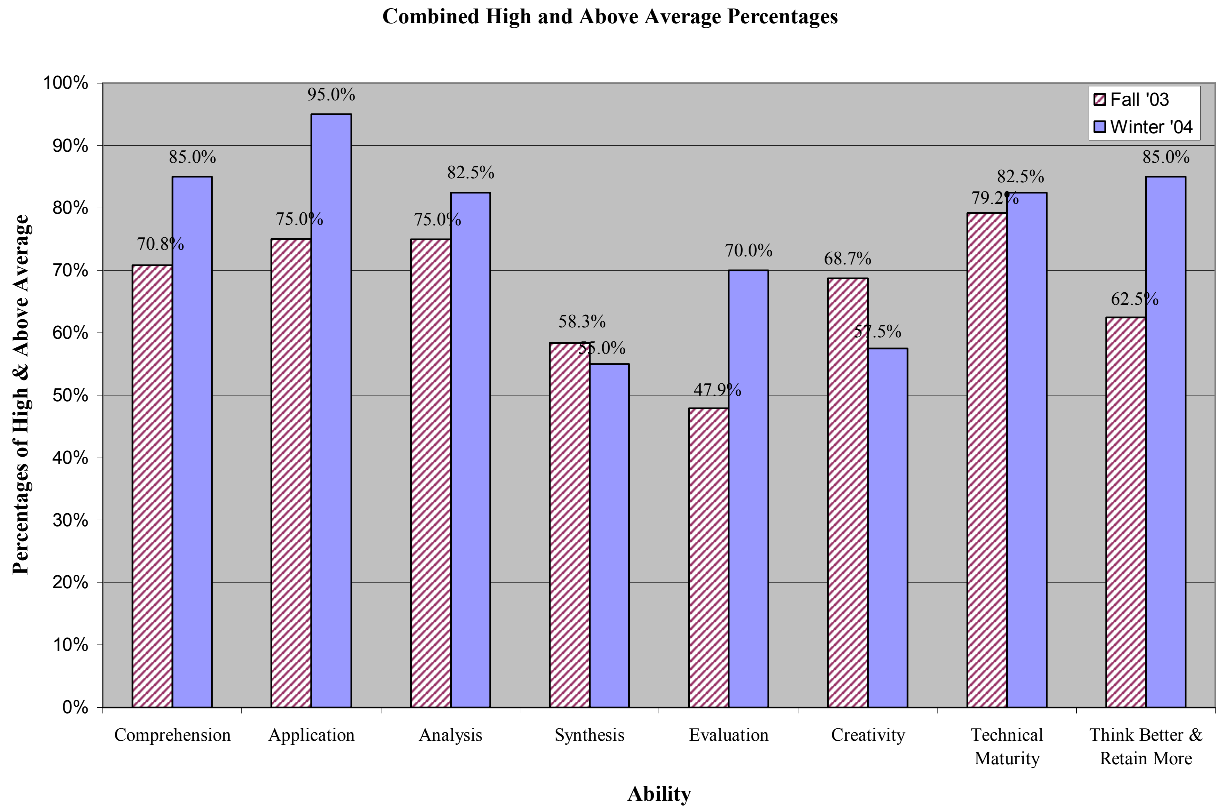

Figure 1: Students' reflections on the contribution of PBL to stated abilities

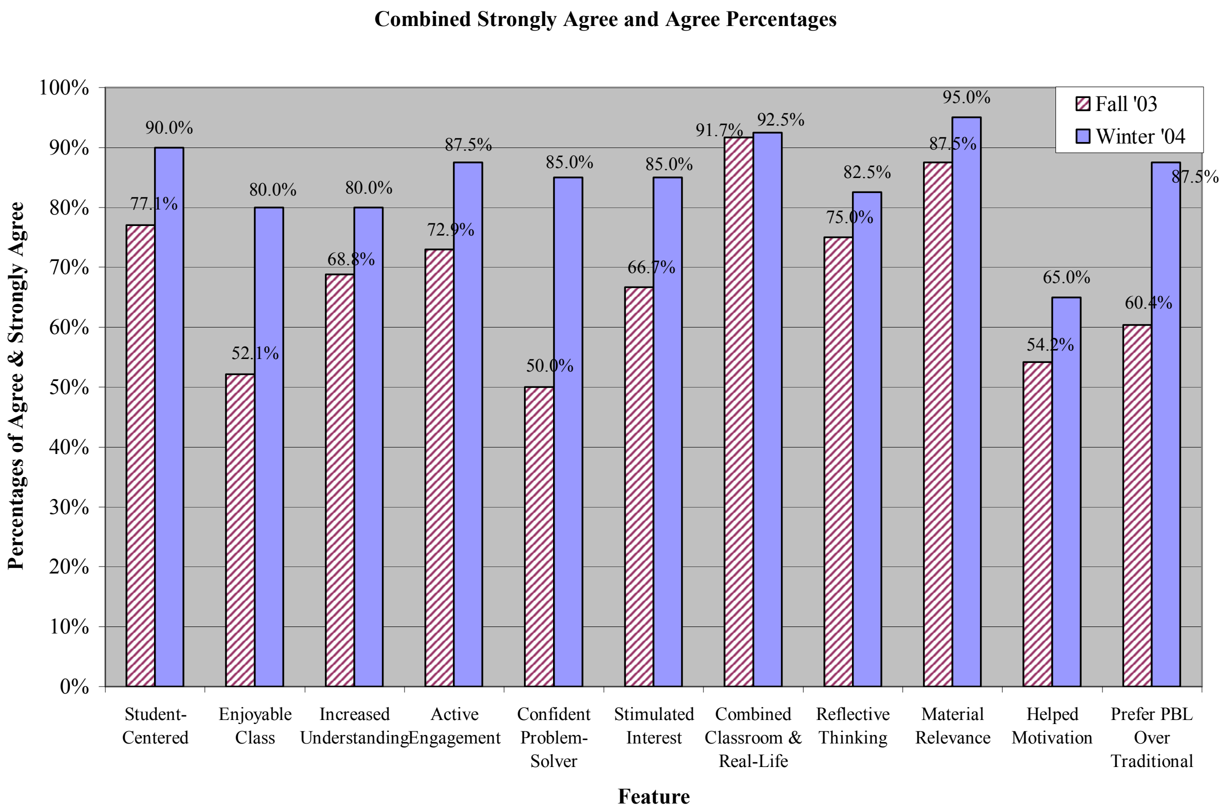

Figure 2: Students' reflections on PBL features

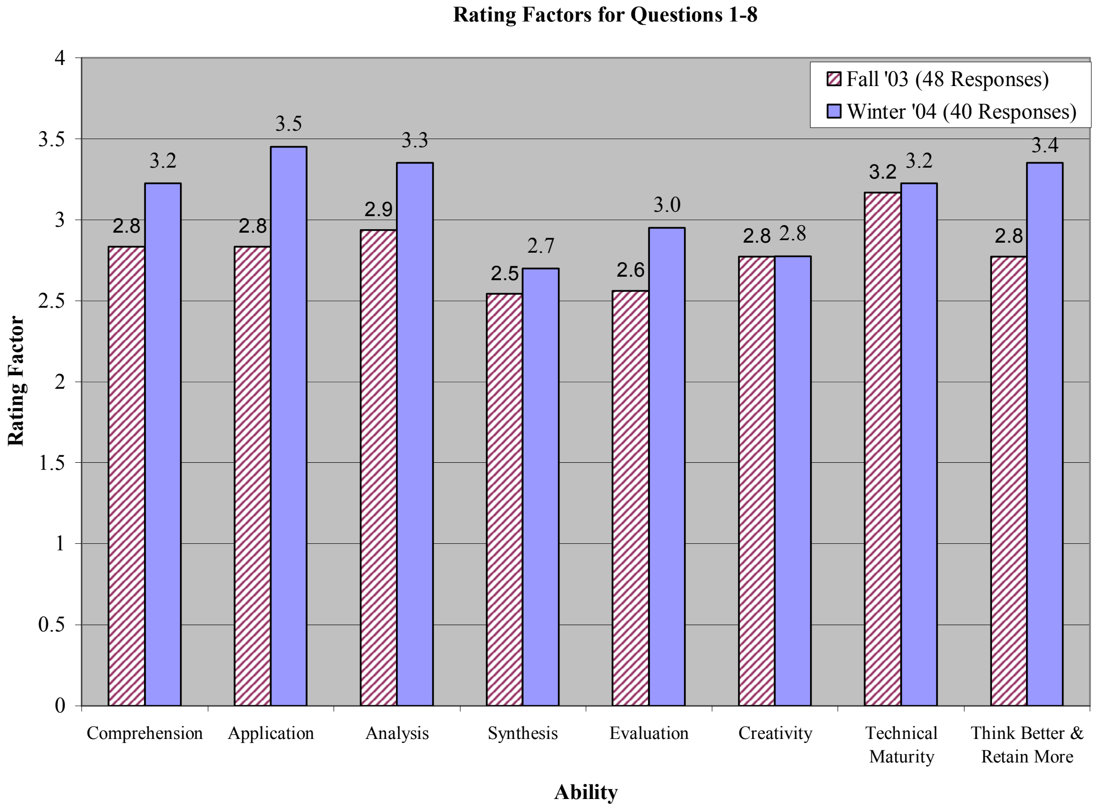

Figure 3a: Rating factors of each ability

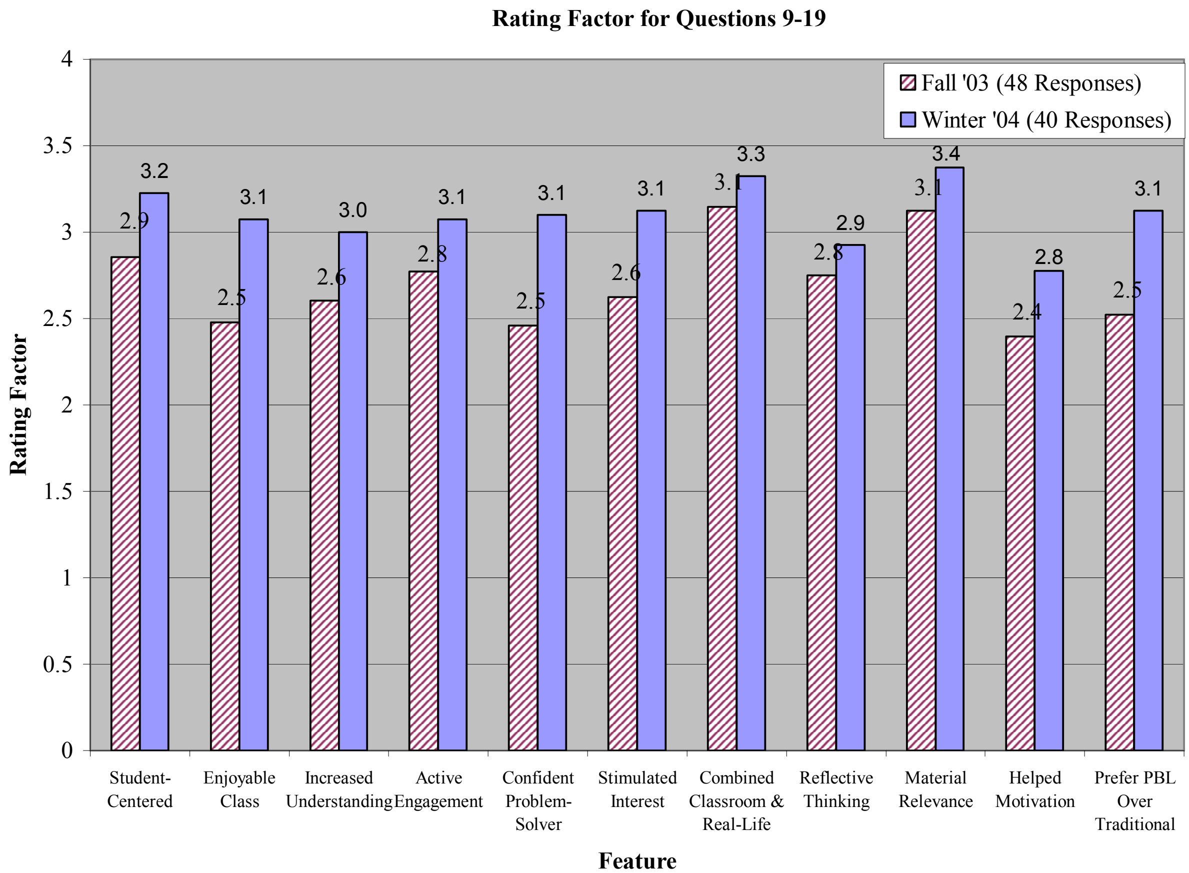

Figure 3b: Rating factors of PBL features

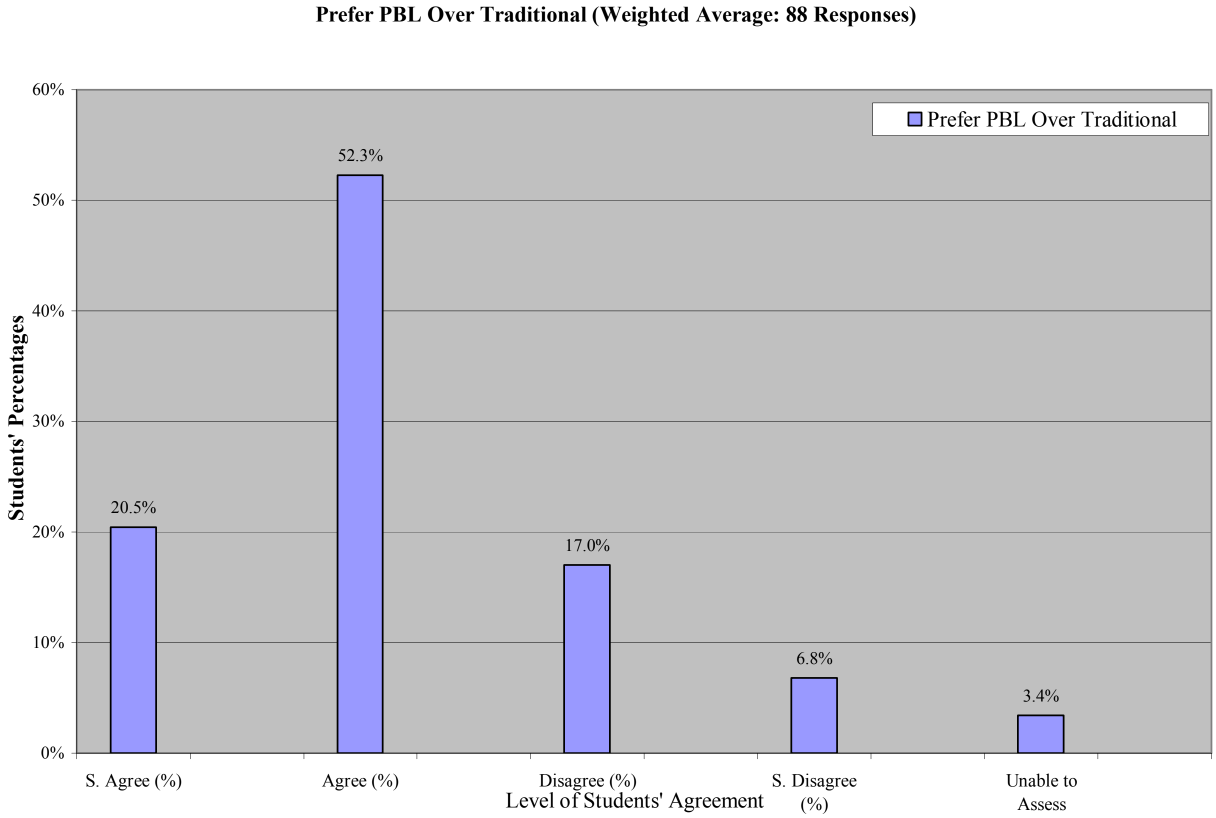

Figure 4: Students' level of agreement for preferring PBL

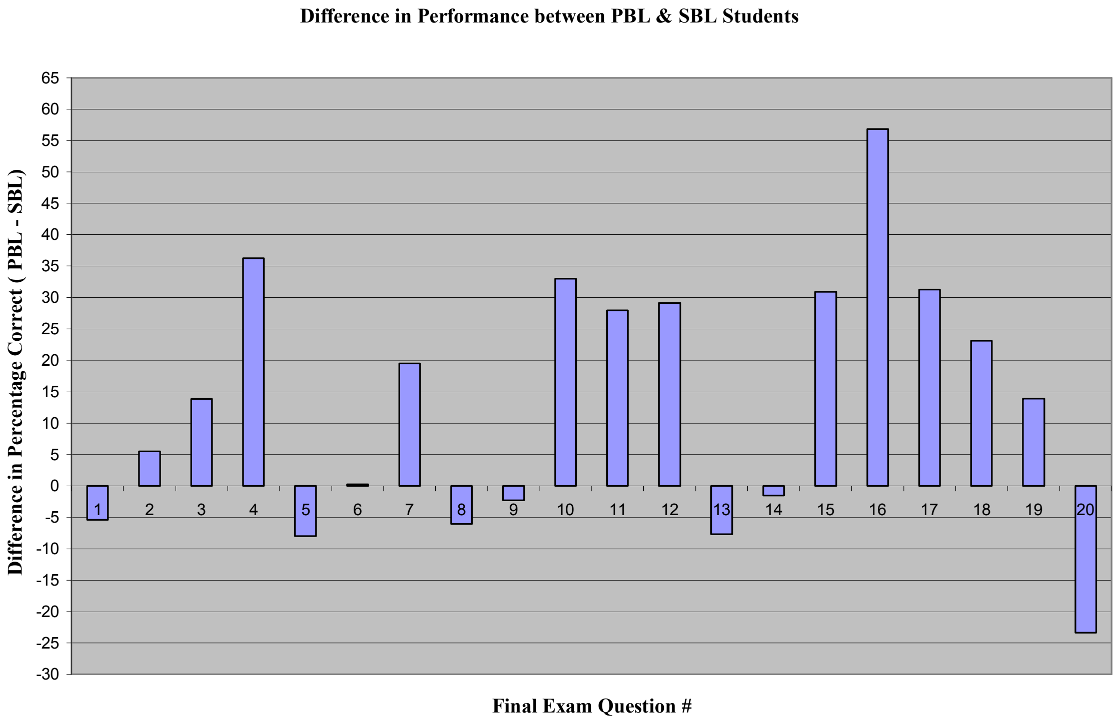

Figure 5: Difference in final exam performance for PBL and SBL-instructed students