Using Problem Based Learning to Teach Thermodynamics: The Good, the Bad, and the Ugly
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Abstract

A problem based learning (PBL) approach was used to teach the first course in Chemical Engineering Thermodynamics (First Law, Second Law, Fluid Property Thermodynamics). PBL was compared to a traditional lecture approach and an active learning approach which were used to teach the same course by the same instructor in terms immediately before and after the PBL term. Student learning was assessed in all three classes through traditional tests specifically structured to assess the first four levels on Bloom's scale of higher learning: knowledge; comprehension; application; and analysis. Student course and instructor evaluations were used to gauge the affective response of Rose-Hulman students to the PBL approach as compared to the other two methods of teaching. According to the exam results, PBL was found to be at least as effective as the other teaching techniques at all 4 Bloom Levels, however teaching ratings were significantly lower for the PBL course than for either straight lecture or active learning approaches. This talk will present a comparison the quantitative results for PBL versus other teaching methods and give the author's opinions as to the other benefits and problems with using PBL in the classroom.

Introduction

Problem Based Learning (PBL) is a new but increasingly popular method for enhancing student learning. On an active-passive learning scale, PBL is far to the active side. The students achieve the course learning goals by working on their own in small groups (teams). The instructor takes a secondary role as only one of many sources of information and as a learning mentor, and the students solve the problems presented to them by learning how to learn – that is by seeking out and using the substantial resources available to them in textbooks, the open literature, and on the World Wide Web. In contrast to having the "basics" delivered to them in a well rehearsed lecture, students involved in PBL are required to seek out the information they need to solve one to several well planned problems presented to them. PBL is commonly used for medical school education and for chemical engineering education at McMaster (http://chemeng.mcmaster.ca/pbl) and is being promoted by the National Science Foundation at the University of Delaware (http://www.udel.edu/pbl) and Samford University (http://www.samford.edu/pbl). Currently there are only a limited number of reports of using PBL for chemical engineering education, though Bucknell University has used the method for at least several years. There are numerous websites touting the use of PBL in various courses.

PBL can be defined as a learning process where the desired course outcomes are achieved through the use of a relatively few (1-5), but well designed, open ended, and real life problems. Solutions to the problems are developed by the students, usually working together in teams of 3 to 5 students. Compared to homework problems and examples used in class, PBL problems are more complex, involve more of the students' reasoning and evaluation skills, and are more open ended. The students first must define what needs to be done, find a solution to the problem scenario, and finally report their findings to the instructor for critical comment and grading. All of the principles and skills that the students learn in a PBL course come from and out of the process of solving the problems. The instructor acts only as a resource, a tutor, and a guide to the student teams.

The secret to PBL, if there is one, is in the problem design and selection. The solution to the problem must take the students through a learning process consistent with the goals of the course and the instructor's desired outcomes for the student. The solution must be of sufficient difficulty to challenge the students to explore multiple solutions and pursue outside resources. The student teams should not be able to solve the problem without significant research and outside reading. Most of the learning and all of the deep learning a student achieves in PBL is attained in the pursuit of a solution. The problem also must be "doable" in the sense that the students must be able to build on their previous knowledge to extend their learning. Problems that are completely beyond the grasp of the students are not good problems for PBL because the students cannot build bridges from their current knowledge or common experience to the new material.

PBL teaches students to become independent learners and, if successful, strengthens their confidence in being able to solve problems on their own. In addition to getting an answer, they can learn the mechanics of how groups work and function best, and they get a broad perspective on problem solving using modern information technology paradigms.

PBL is not a new discovery in teaching methods, but rather has been rediscovered as a method especially apropos for this day and age. There appear to be at least three reasons for a rise in the use of PBL in recent years. First, there has been a sea change in the way that information is transferred among people. This is mainly due to the internet, the generation of electronic documents, and the ability to research topics using powerful search engines. Information is at the fingertips of almost anyone instantaneously and single source experts are not as valuable as they once were. The professor is no longer the only central repository of information on a particular topic, and a "guide on the side" is a better description of the educator's role than as a "sage on a stage."

Second, the explosion of new scientific information has made it almost impossible for textbooks to keep up with the state of the art in science and engineering. One can clearly learn more about current techniques in molecular biology by using the most recent methods published on the internet than by reading about what are often outdated methods in a textbook. (For any flaws it has, instant publishing has the advantage of speed over any other method of conveying information.)

Third, steady research into the process of learning has shown that the "transmitter – receiver" model of learning where the professor is the transmitter and students are passive receivers is clearly incorrect and leads to poor learning. This type of teaching is sometimes no more than a "get it and forget it" method designed to get the student through the next test. All the current evidence indicates that learning is a complex process that requires student involvement in an active role. PBL addresses the use of modern information transfer methods, up to date learning, and active student involvement. The problems the students tackle can be relevant, challenging and solvable at the same time.

Unfortunately, not much hard data exists to prove that PBL teaches students more than the more normal didactic approach of lecture and listen. However, most instructors who have used PBL are convinced from personal experience that PBL is a better method for engaging students and leads to longer retention of the material. The PBL method leads to substantially more interesting classrooms especially when the material is dull, tedious, or especially difficult to comprehend.

Problem Design

Since the success of a PBL learning experience hinges on the problems that the learner addresses, care must be taken to present well conceived and designed problems to the students. The problems cannot be wasted-- there is little room for error. Problems must be conceived so that the desired course learning outcomes are embedded in the problem itself, and designed so that the students must take a path through the principles and skills the instructor wishes the students to learn. If the problems "miss" the desired outcomes, or the students find a path through the problem but around the desired learning outcomes, there is little opportunity for the instructor to intervene by "adding a lecture" or working out another example for the students.

There is little guidance in the literature as to the process of problem design for PBL courses, but my brief experience with PBL and word of mouth advice from colleagues at other institutions has led me to the following list of suggestions:

- There should 3 to 4 problems for a 1 semester course (40 – 45 (50 minute) meetings). The students will procrastinate too much on one or two problems, and more than 4 problems does not give them sufficient time to work on the problems, there are often many (desired) dead ends and false starts and these take time to work through.
- The problems should have overlap and be connected as much as possible. PBL is a building process. The first problem should build on student experience and common sense, and the subsequent problems should build on the foundation laid by the first problem and each other. Overlap and looping back reinforce new material and principles as the students see the ever widening applicability of what they already know to other problems.
- The problems must encompass all of the learning outcomes desired by the program and the instructor. There will be little or no opportunity to "add knowledge" to the class by special lectures and the instructor will become keenly aware of the failure of the lecture method to educate the students to the depth achieved by the PBL problems.
- The problem assignment needs to be carefully designed in terms of deliverables. Students will need to be held accountable for hard numbers and for preparing a report. The tendency is for students to be qualitative and vague - the problem assignment should make it clear what numbers are required.

- The problem assignment should have intermediate goals. Students are poor at pacing themselves and will almost certainly wait until the last minute to work on the assignment if they are not held to intermediate reports and goals. This is especially important for students who have become passive learners and are used to being driven by the instructor. The goal here is ingrain the habit of schedules and taking on intermediate tasks into the students' way of doing things.
- The problem should encompass and address different (Bloom's) learning levels. Some of the assignment should be aimed at increasing student knowledge, some comprehension, some application, and some analysis, synthesis, and/or evaluation, the latter two levels will probably be reserved for advanced courses.

Course Structure

Due to administrative constraints in most institutions, PBL must be designed to work within the normal 50 minutes - 3 or 4 times a week framework. Rarely will the whole institution adopt PBL and lecture courses are only manageable in this framework. Students should be told that they are expected to meet outside of class (homework) and should be encouraged to use virtual meetings or other electronic meetings to accomplish their goals. The students do not have to do everything together, but they do need to have face-to-face time at least several times a week. Scheduled class time is well designed for those meetings.

Class meetings should not be dominated by lectures. There is a certain tendency to feel that the students must be busy every minute in class or that time is being wasted, but if the students are productive only 30 -50 % of the class time they will still be doing and accomplishing more than a typical lecture class. If the technology is available, the students should be encouraged to cruise the internet during class, for that is one of the main ways they will gain basic and background information for the project.

Laying the groundwork for a particular problem should take no more than one 50 minute lecture period. After that the students should be encouraged to seek information from the instructor by asking for specific topical lectures or by asking questions via e-mail or course interaction programs like "Blackboard" or "Angel" sites, the latter being anonymous. The students should not be getting basic knowledge (Blooms Level 1 and Level 2) from the instructor. They may need help with higher level (application and analysis) questions, but the answers should be returned in the form of principles and not as a direct answer to the particular problem. The students must solve the problem.

This is all very difficult to balance, but less information after the project has started rather than more is the general rule of thumb for PBL classes. Because students are used to being "spoon fed" (true even if we do not like the implications of the term) they will naturally find lectures more familiar, relaxing and enjoyable, and it is to be expected that they will complain about the feeling of being left alone without guidance. They may even rebel (as my class did) against the methodology. These are all common responses to PBL.

Thermodynamics Course Structure

I spent about 2 months in the summer setting up and planning the thermodynamics problems for my course. (1 -2 hours a day.) The basic model I used for the course structure can be represented by a pyramid diagram as shown in Figure 1.

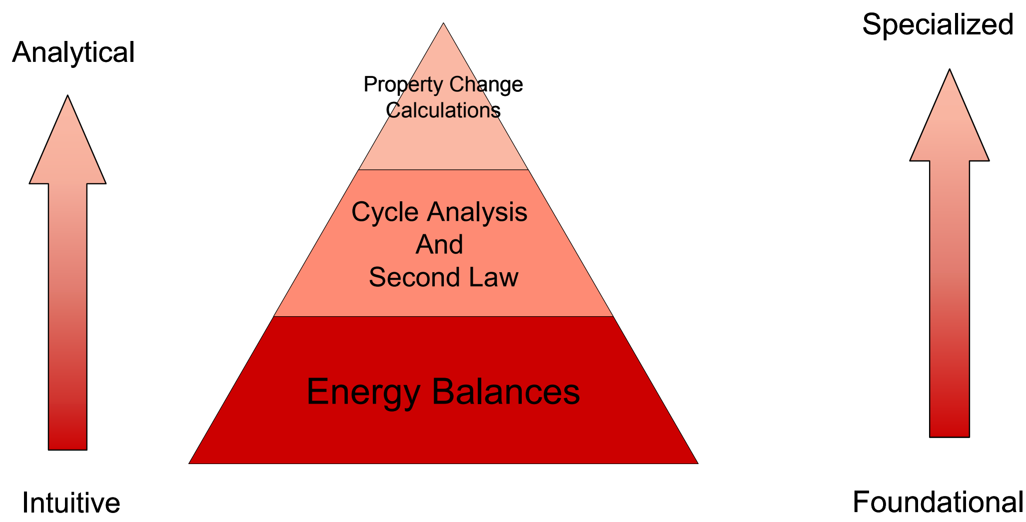

Figure 1. Course "design" for basic thermodynamics course.

Course Goals and Desired Student Outcomes

There are three goals to the course. The first and most important goal is that students learn the concept and practical use of the energy balance equation. Among the main desired student outcomes are that they commit the energy balance to memory, that they can properly eliminate terms from the energy balance to fit a verbal scenario, and that they can solve the simplified energy balance for both steady and unsteady systems.

Once the students have mastered the first law, a second goal is addressed, namely that they learn to deal with second law analysis (entropy change calculations) and apply the second law to find the limitations of processes and equipment used for converting work to heat and vice-versa. The practical systems the students are expected to understand are classical power and refrigeration cycles. Outcomes are that the student should be able to design a cycle to accomplish a thermodynamic goal, should be able to compute local and global entropy changes for processes, should be able to find theoretical and real cycle efficiencies, and should be able to recognize when a proposed design is thermodynamically impossible.

The final goal is for the students to learn various methods for estimating and calculating property changes with real fluids. The student should be able to compute a property change and absolute property values given thermodynamic tables, an equation of state, or reduced property graphs available in the literature.

Learning Progression

As the student progresses through a problem, the learning process (should) move from the intuitive to the analytical. The students should find that in the beginning of the course they will rely on their natural understanding of energy as a "thing" to initially guide them in their project, progressing to using the energy balance equation to compute and confirm their intuition. Intuition is less valuable in the second law and property changes calculations (Goal #2) so one has to completely rely on equations, tables, and/or graphs for answers for most of the second and third goals in the course.

This general approach was cast into a course plan as shown in Figure 2.

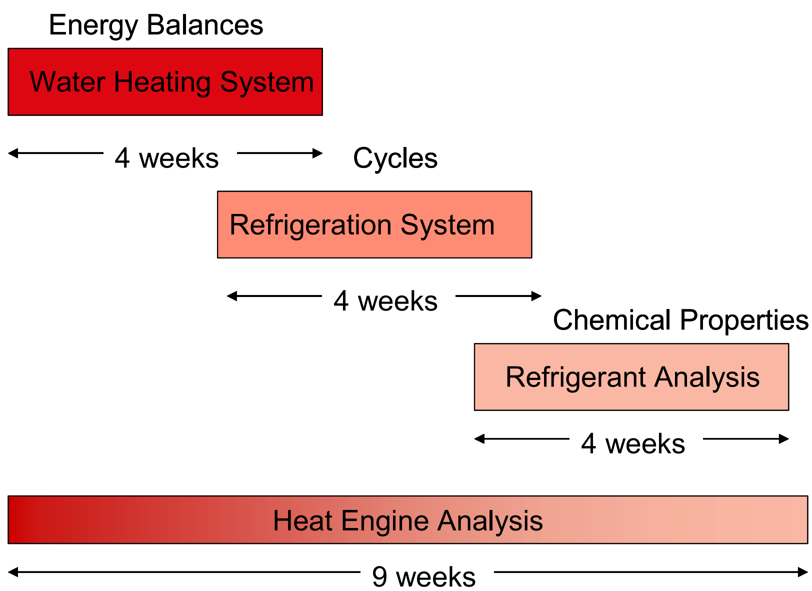

Figure 2. General course plan for thermodynamics

The first 3 weeks of the term, (10 weeks) the students worked on a water-heating system design, which included both steady-state and unsteady state features. About the 4th week the students were given an additional problem, in this case a refrigeration process problem where they analyzed a refrigeration system designed for a particular purpose. Meanwhile the students finished up the first problem. About the 6th week they were given a problem in refrigerant design to see what would happen if one changed fluids in the refrigeration system described in the second part of the course. In my original plan the students were also given a hands-on problem of designing and building a toy heat engine with a kit we put together for the students. The object was to make the course more "fun" and at the same time address their need to build and touch something. They were asked to take a digital video of their design and show how it functioned and to do a simple thermodynamic analysis of the process. (Later, due to lack of interest on the students' part they were asked to analyze a "dipping duck" the apparent perpetual motion machine many of us have seen.)

Implementation

To implement the course plan, the students were organized into 7 teams of 4 students each and were asked to take on team roles and develop a team contract which laid out the expectations the students had for each other in terms of participation. The students were given brief learning style tests to put them into groups which had the widest possible range of learning styles. They were then asked to take on roles of Facilitator, Notetaker, Timekeeper, and Devil's Advocate and coached as to what each role entailed and how it fit in to overall team and team meeting structure (1).

Class was conducted in a casual atmosphere, organized around tables and not rows of desks. The instructor roamed around the room answering questions and looking at the information the students were finding on the World Wide Web and in books and papers. Once or twice a week the instructor presented a short slide show (20 minutes) or other form of lecture to the students when they asked for some information on how to look for something. There was little "moment to moment" direction given to the students, nor were the students given much information on milestones, except for when the problem reports were due. (In retrospect I think it was a mistake to not have more intermediate goals. The students were only juniors and probably were used to solving shorter (homework) problems. My feeling is that they had trouble pacing themselves through these longer problems and would have benefited from some instruction on dividing up a problem and organizing a "plan of attack".) The students were expected to come to class but were free to come and go to the library or the lab to look over equipment related to the machinery they were asked to design. A few talks were given by the instructor in the laboratory when requested or to start a new problem. (For example we have a refrigeration unit in the lab and the instructor demonstrated and lectured on the unit.) A course website was made available to the students which had the posted problems, certain key internet links to information, and the course syllabus and slideshows. A midterm affective survey was given to assess the students' feelings about the course and how things were going.

Assessment

The students' course grades were determined from the technical accuracy and quality of the group reports (55%) and from term exams (45%). The reports were not specifically scored for writing style or grammar but writing feedback was given on both of these. The reports were graded only for technical content. The students also did "360 degree" peer evaluations, evaluating each other and including self assessment of their own level of effort and participation on the problems. These were used to determine the individual student scores from the group scores.

Projects

Reports were requested on 4 projects. (The project statements typically took up more than a page so I will only give a brief statement about them here.) The first project involved the design of a hot water system to supply hot water to a chemical plant. Demand data was given to the students in the problem statement and they were told the temperature of cold water available to the plant. They were told to design a hot water system and analyze their design using an energy balance. They were told to prepare a written report of 1000 words or less that contained appropriate graphs, charts, and tables that gave quantitative and qualitative predictions of how well the system will work.

The second project involved researching refrigeration systems/heat pumps and the refrigerants used in 1935, 1985, and 2003 (today). Two reports were requested, one a more qualitative report on the history of refrigeration, the differences between refrigerators, freezers and air conditioners, and the general way one analyzes an ideal refrigeration cycle. The other report, more quantitative, was to focus on the calculation of the coefficient of performance of each of the three types of refrigeration cycles using each of the three types of historical working fluids. An additional request was for them to analyze the effect (technical ramifications) of putting a 2003 working fluid into a refrigerator made in 1985. A third request was for them to discuss the thermodynamic properties of a working fluid that make it especially good as a refrigerant.

The third project asked them to suppose their job was to develop the next generation of refrigerants. They were directed to find existing chemicals which had appropriate thermodynamic properties but were not being used as refrigerants and to explore the use of chemical mixtures as possible refrigerants. They were specifically asked to calculate P,V,T behavior and calculate changes in internal energy, enthalpy, and entropy when the temperature and pressure were changed and compare their calculations to the best available data.

The fourth project (worked on for the whole term) asked them to design, build, analyze, and document a working "heat engine" based on a kit we made available for them which used the heat from burning "Sterno" to spin a small can containing liquid water.

Exams

Three exams were given, mainly because I was trying to compare the students' performance on "typical" exams to the exam performance of classes taught using ordinary lectures and lectures with active learning activities sprinkled in. The exams tested the students on the first 4 levels of Bloom's scale, namely knowledge, comprehension, application, and analysis.

A "knowledge" question would be phrased as follows (closed book):
"In the space below write out the complete energy balance using the symbols typically used in a textbook. Place all system side terms on the left hand side and all inputs and outputs on the right hand side."

A "comprehension" question would be phrased as follows: "Give an example of a scenario where each of the following terms would be important" (followed by various terms from the energy balance equation like rate of work out, Hin, etc.)

An "application" question would be "A tank of water is being filled while it is being heated with a 10 kW electrical heating coil … etc. Develop the appropriate simplified energy balance for this scenario. Show and justify each step you use to arrive at your answer."

An “analysis” question would be: “Considering the scenario above, find the filling rate in liters per second which would be required so that the tank would reach 80 C just as it became full.”

Questions of similar tenor were used to assess the students for the second law and thermodynamic properties portions of the course, knowledge questions focusing on facts, comprehension focusing on meaning, application focusing on procedure, and analysis focusing on solution.

At the end of the course, the students were given the normal institutional surveys to gauge their affective responses to the course and instructor.

Results

The “Good”

Reports

For the most part the students were able to produce and present solutions and write acceptable reports on all three problems. Technically speaking, the reports were very good and there were few errors in their analyses. (The writing was somewhat rough, but our students don’t get critical feedback in their writing styles until their senior year and these students were mainly juniors.) I was not unhappy with any of the three reports prepared by any of the student groups, however I was perhaps disappointed that they did not show as much in-depth thinking that we would like from our students or go very far beyond the stated requirements. Overall the reports were good.

Tests

The average test scores received by the PBL class compared to a traditional lecture class the term before and an active learning class the term afterward are shown in Figure 3.

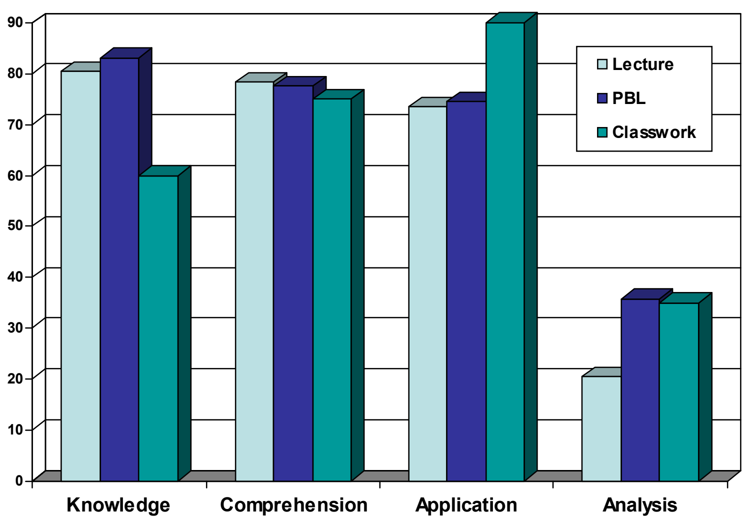

Figure 3. Test results. The abscissa shows the average percent score given to each class on each of 4 types of questions for 3 midterm tests.

Tests were designed to address and distinguish Bloom's learning levels. A portion of each test was devoted to assessing the students' basic knowledge, a portion focused on comprehension, a portion focused on application, and a portion focused on analysis. The average score (as a percentage) for each level was computed for each of the three teaching methods.

The bottom line is that despite slight variations there was no easily discernable difference between classes taught using PBL, lecture, or active learning exercises sprinkled into the course. The active learning exercises group scored lower on basic knowledge skills than either straight lecture or PBL students. All three groups appeared to have similar comprehension of the principles, the class taught using active learning exercises seemed to be better than the other two at application of the principles to problems, and the lecture group was less skillful at analysis (which involved making calculations and conclusions from them in an exam environment). Student t-tests were done to compare the average scores on each type of question among the three teaching methods used. In no case is the difference between the scores statistically significant ($P<0.90$). However, it may be true that classes taught using active learning did not cover the range of information that pure lecture courses did (knowledge), but do focus better on comprehension from the way problem solution techniques are taught. None of the classes including PBL did very well at analysis even though this was taught in both the lecture and active learning courses and was included in the PBL problems. There appear to be some unexpected weaknesses in math and modeling skills issues that go beyond the course material -- or the instructor may be expecting too much from the students. (Thermodynamics is the first time the students are required to combine what they learned in calculus to solving a "real" problem.) Lecturing appeared to be the least effective way of application and analysis skills, both of these scores for the "lecture" class were lower than the "active learning" and "PBL" classes. This is something we need to look at further, first to find out if this result is real and then to find out the root cause. A hypothesis is that students develop analytical skills better from solving problems than they do by watching someone else "do examples".

The "Bad"

From the instructor's viewpoint there were some negative aspects to PBL especially concerning how the students operated and the attitudes they displayed. Without the "homework every week" and "test every 3 weeks" structure used in many of the lower level courses, the students had a hard time pacing themselves in an open ended situation. Often they did nothing but talk in class and then they would openly complain that they did not know what to do or that they had no time to do things. They appeared to be used to being told what to do on a daily and weekly basis and were uncomfortable coming up with their own schedules and milestones.

The PBL approach also exposed that students had not yet developed leadership and organizational skills, nor were they good at planning or taking notes in meetings in or outside of class. In addition, the students were poor at using resources to find information. They expected to receive all the data they needed and the equations they were supposed to use from the instructor. Twice, failure to provide information when it was requested erupted into open rebellion in class despite the fact that the material requested could easily be found using common search methods. They were often unable to find the right section of the text to match the problem they were currently working on, apparently because they were used to being directed to the chapter and page of interest for the daily lecture.

The students did not want to evaluate information in the literature or analyze any data that might help them with their problem. They had problems synthesizing a solution from partial information obtained in the book, lecture slides, or on the internet.

Basically, the students did not like PBL from the beginning. From the first day of the course they did not like the idea that they were being asked to learn on their own and they were vocal about it from the very first day of class. Mid term evaluations of the course showed that they already did not like the course approach and it appeared that they were trying to make the course fail. I tried my best to appeal to their professionalism and for them to have faith in themselves and in me that this method could work but was unsuccessful. The reaction on their part was discouraging for me as the instructor.

The "Ugly"

The worst part of the course was the student evaluations. Though many students were willing to make lengthy comments, only a very small number of students had anything complimentary to say about the course, most were convinced that they learned nothing, I did the course this way because I was lazy, that they needed me to teach them the basics first, and that they couldn't learn the basics on their own while trying to solve a problem. At Rose-Hulman, student evaluations of the course ask about student learning, mainly "did they feel they learned a lot", the course, "did they enjoy the course material", and the instructor, "did she or he teach the course well". Not being a particularly popular or skillful teacher, I normally score in the 3.0 (average) to 4.0 (good) range on a 5 point scale probably about a 3.3 to 3.9 on average, a little lower than the Institute average. In this course I received 2.21, 2.38 and 2.38 scores (below average) scores in the three categories. The very next term using traditional teaching methods, I received scores of 3.71, 3.76, and 3.76 in the same categories (Figure 4) teaching the same course with the same learning objectives.

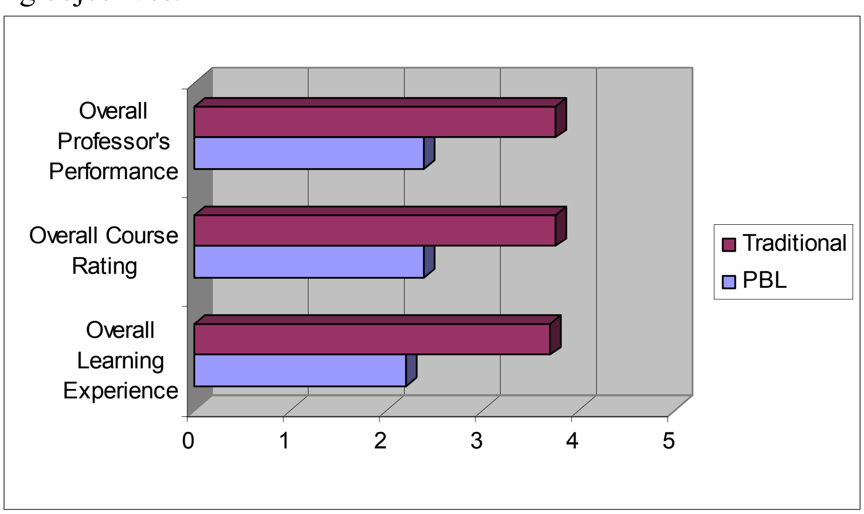

Figure 4. Comparison of student scores on course assessment when using traditional and PBL teaching methods.

Consistent with their written comments, the scores reflected the idea that the students did not feel they learned the material, that the course was not interesting, and that I wasn't prepared to teach the course. This was the worst student evaluation I received in more than 20 years of teaching!

Discussion

Having used it to teach, I believe there are two incontrovertible facts about using PBL in a junior level first course in thermodynamics at Rose-Hulman. The first fact is that the students using PBL perform just as well on thermodynamics tests as do their counterparts taught using conventional lecture and/or active learning in the classroom. The scores on knowledge, comprehension, and application were equally acceptable regardless of which teaching approach was used. The students were able to remember facts about energy balances, refrigeration cycles, and thermodynamic properties just as well when they learned about them by reading on their own and applying what they read to a problem, as they did by listening to the instructor lecture and work examples or by them doing class activities on a regular basis.

The second fact is that the students' affective reaction to using PBL was very negative. The course and instructor ratings were the lowest this instructor has ever received by nearly one point on a 5 point scale. Considering the class rebellion to the method, it is surprising that the test scores were as good as they were, but apparently the class did try (and succeeded) in learning the material despite their distaste for the method.

By way of "Lessons Learned", there are a few things to say. First, I found preparing for PBL to be significantly more work than normal preparation for a course as suggested in the literature (See Wankat (ref. 2)). For my course I had a very solid list of course goals and outcomes. Setting up and testing 3 solvable problems that addressed these goals took some work. Preparation is necessary. Using PBL offers less chance for midcourse adjustments, making the teaching more tedious. You simply cannot slow down or increase the pace with pre-formulated problems. The problems are the key for the instructor to being satisfied with the learning.

Second, I was taken off guard by the open rebellion I faced. Simply put, the students demanded that I lecture to them and when I declined, that made them mad at me and the course. Cries of "it's not fair" or "we don't know where to start" were common in the class. I was not prepared for a battle with the students, thinking it would be a fun experience for them. Though I remained positive and was excited about the quality of learning taking place, the steady negative feedback from the students was difficult to deal with.

The negative reaction was especially hard to take when I observed the results of tests to measure student learning were good and clearly equal to the results from more direct teaching. Not only that, but from talking to them throughout the process, it was apparent that the students gradually became better informed as well as academically better engineers who learned interesting things about the problems they were studying and also about things well outside the original intent of the problem. To see someone learning and not believe it, was discouraging. To see them become independent learners and not enjoy it was disheartening.

Recommendations

Having been through this, I would strongly recommend PBL but never recommend it to untenured faculty. The blow to my ego has been difficult to handle. In a small school like Rose-Hulman you teach the same students multiple times and that "they hate me" feeling is everyday. The repercussions for me in terms of tenure are also significant. Perhaps if my normal ratings were 4.5/5.0, low scores in a single "experiment" would not be so difficult for the administration, but I believe an average teacher should beware of the drop in ratings that might occur. This reaction by the students can have an influence on the way my overall evaluations are viewed.

A couple of adjustments to my program may have reduced the student backlash. First I was too optimistic about how the students would receive this approach and didn't prepare the way very well. Doing it over, I would spend much more time explaining the benefits to PBL. More importantly, I could have provided more instruction on how to learn on your own (as ironic as that may seem). I was basically asking them to learn how to learn and that made them uncomfortable. I underestimated how dependent on being told exactly what to do the students actually were. They evidently needed to be weaned off of this approach rather than going "cold turkey". I am not sure spending time on this would have brought about the desired result any faster, but it probably would have been more comfortable for the students. Another way of saying this is that I should not have let my enthusiasm for PBL blind me to how the students were feeling about using a new method of learning.

All that said, there is no doubt in my mind about the value of PBL. As we continue in the "information age", lecture teaching, even with active learning exercises folded in, may become an increasingly dated method of teaching. There still remains before us the need to imbue our students with the abilities to learn to learn and the desire to discover things on their own. Problem Based Learning should become one of the main methods for promoting those goals.

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