Annals of Biomedical Engineering, Vol. 34, No. 2, February 2006 (© *2006*) pp. 217–225
DOI: 10.1007/s10439-005-9034-z

Fostering Integrative Problem Solving in Biomedical Engineering: The PBL Approach

WENDY C. NEWSTETTER

Georgia Institute of Technology Atlanta, GA

(Received 10 May 2005; accepted 9 September 2005; published online: 16 February 2006)

THE CHALLENGE

The rapidly changing field of Biomedical Engineering poses particular challenges for engineering education. On the educator front, medical technology changes at such a rapid pace that it is hard is for BME educators to keep abreast of all the advancements in the related fields of molecular biology, computer science, tissue engineering, and genetic engineering. Further, since textbooks for undergraduate BME courses are few and far between, instructors either have to patch together course material from multiple sources or use textbooks from related fields which often involves skipping over a great deal of irrelevant material.

On the student front, the learning challenges are immense. The field demands that students develop multidisciplinary skills and knowledge in biology, chemistry, several engineering subdisciplines and computer science. They need the modeling and quantitative skills of traditional engineers, but also the qualitative systems understanding representative of a more biological approach. They also need exposure to the clinical side of the discipline where design applications meet the real world of patients and doctors. In short, students need to be fully conversant in three intellectual traditions, which are often at odds with one another and have historically been taught by distinct faculties. For an individual to reconcile these disparate practices and historically separated intellectual traditions she/he will need cognitive flexibility and true integrative thinking—appropriate learning goals for a BME curriculum.

In an attempt to foster such integrative thinking and interdisciplinary problem solving strategies, certain BME programs[*1] have adopted a model of learning and a set of educational practices that have been used in medical education for more than three decades. Referred to as Problem-Based Learning or PBL, this approach draws on constructivist pedagogy, which assumes that learning is the product of both cognitive and social interaction arrived at through authentic problem solving.[9] The classic medical version utilizes clinical problems designed to support free inquiry and the development of diagnostic problem-solving skills. In recent years, PBL has begun to find its way into undergraduate science and engineering education.[6,7,16–18,20] In the both cases, the freedom to identify one's own area of inquiry encourages student-directed learning and increased learning gains.[4,9]

In the BME context, problems are derived from current interdisciplinary research areas such as tissue engineering, imaging and gene therapy, from clinical settings or from industry focused areas like device design and development. Problems can also be developed from headline stealing topics such as mad cow disease or decisions concerning life support systems in compromised patients. Problems can be designed to foreground the complex ethical and policy issues that accompany the development of innovative technologies. All such PBL problems have the possibility of exposing BME students to the fast paced nature of technological change and the requirement for innovative problem solving across disciplinary borders. More importantly, however, these kinds of problems require students to engage in integrative thinking across disciplinary lines while helping them build the inquiry skills foundational to life-long learning.

At the final Whitaker Foundation Educational Summit in March 2005, 80 or so faculty members from BME programs in the United States and abroad attended workshops on understanding and then instituting PBL approaches. The following sections attempt to capture the flavor of the interactions that constituted the PBL workshop, on the one hand, in terms of the questions asked by participants, but to also explain how the PBL approach has been instituted in the graduate and undergraduate curricula in the Department of Biomedical Engineering at Georgia Tech (for a more in-depth discussion of the design and development of PBL for engineering education see Ref. 12). These sections can serve two purposes: to offer a model for other programs to

Address correspondence to Wendy C. Newstetter, Georgia Institute of Technology, Atlanta, GA, 30332. Electronic mail: wendy@bme.gatech.edu

[1] PBL has been fully implemented in engineering classes at Aalborg University in Denmark for more than 30 years and at Twente University in the Netherlands for more than 10 years.

0090-6964/06/0200-0217/0

follow or to serve as a jumping off point for experimenting with PBL in other contexts and other curricula.

WHAT EXACTLY IS A PBL APPROACH? AND HOW IS IT DIFFERENT FROM OTHER EDUCATIONAL APPROACHES?

PBL is just one of the several methods that form a constellation of approaches referred to as *anchored instruction*. Other anchored instruction approaches include project-based learning, challenge-based learning and inquiry-guided learning.[11] In each of these approaches, knowledge accrues through constructing a solution to a complex, ill-structured problem. Learning is not linear but proceeds as the student explores the problem space. If different student teams are tackling the same problem, they will probably choose different routes and very possibly arrive at different solutions. In the process, multiple topics and knowledge domains are encountered, which helps the student build a more extensive, integrated and flexible knowledge base.[3,9] Repeated exposure to the same topical or content area in different types of problems gives students the opportunity to practice seeing through a complicated "cover story" down to the deep principles. This approach contrasts with most textbook-driven learning, which focuses on concepts presented linearly but in isolation from other forms of knowledge. Thus it would be highly unlikely to have ethics issues as part of a biotransport class. In addition to the coherent but flexible knowledge structures that can accrue from solving a complex problem, studies have shown that PBL students learn considerably more than their peers do in traditional learning environments about how to solve problems, how to manage their own learning, and how to work with others,[8,14,15] all industry promoted skills that will be critical in the workplace.

While all post-secondary engineering classrooms use problem solving as part of a pedagogic package, PBL goes beyond homework problem sets or occasional real world problem applications in the classroom in providing a systematically organized and sustained learning environment referred to as a *cognitive apprenticeship*.[5,12] Like the novice in a traditional apprenticeship, the PBL learner engages in a set of repeated learning interactions that replicate the activities of a more experienced practitioner but with the guidance of a facilitator. This facilitator, like the master tradesman, models and coaches or *scaffolds* expert problem-solving strategies within the group. So while PBL is most commonly conducted with small tutorial groups, the actual model of learning derives from a traditional one-on-one apprenticeship in the trades. In both cases, the learner repeatedly practices the integrative reasoning skills fundamental to complex, open-ended problem solving while building a knowledge base in engineering and the life sciences.

WHAT HAPPENS IN A PBL CLASSROOM? HOW IS A PBL COURSE STRUCTURED?

The Group Cycle

The basic learning unit of the PBL approach is the tutorial group, comprising six to eight students and a facilitator/tutor. In the Georgia Tech program, students are randomly assigned to groups at the beginning of the semester with attention to balancing gender, race and ethnicity in a way that would be consistent with research on collaborative learning.[**2] Specially designed classrooms with four writable walls, which only accommodate 10 people have been designed for these groups which meet twice weekly for an hour and a half each session. The PBL session follows a protocol in which students articulate and apply what they know or have learned through out-of-class self-directed inquiry, use this new information to generate hypotheses, models and ideas, and identify new areas for inquiry to be conducted before the next session. These activities model the reasoning strategies the students are working to master. Figure 1 depicts this interactive learning cycle.

An essential element of this reasoning process is for students to identify what they do not know but need to know to solve the problem. This identification process motivates students to take ownership of their learning because they have recognized focal points for inquiry themselves rather being given them by the instructor or the textbook. Also, since each member is responsible to the group for learning the material well enough to apply it to the problem, they are individually challenged to do a good job out of class in their inquiry. By repeating this cycle in each session, the group comes to frame the problem through analysis and solve it through application of new information brought into the problem space by all of the team members. At problem closure, students reflect back on the whole problem cycle to see how all of the newly acquired concepts and activities have resulted in a solution.

The Problem Cycle

Over 3 or 4 weeks, each problem undergoes three transformations. First, the problem statement given to the group is transformed into a problem resolution, which the group has defined and refined. This solution is then transformed into a short presentation delivered to other groups who have worked on the same problem and to invited "experts" in the problem domain. Lastly, the solution is transformed into a technical document. Each of these transformations serves various learning goals. The transformation from problem

[2] So far, in these assignments we have not addressed differing learning styles or personality profiles as measured by Myers-Briggs or other instruments.

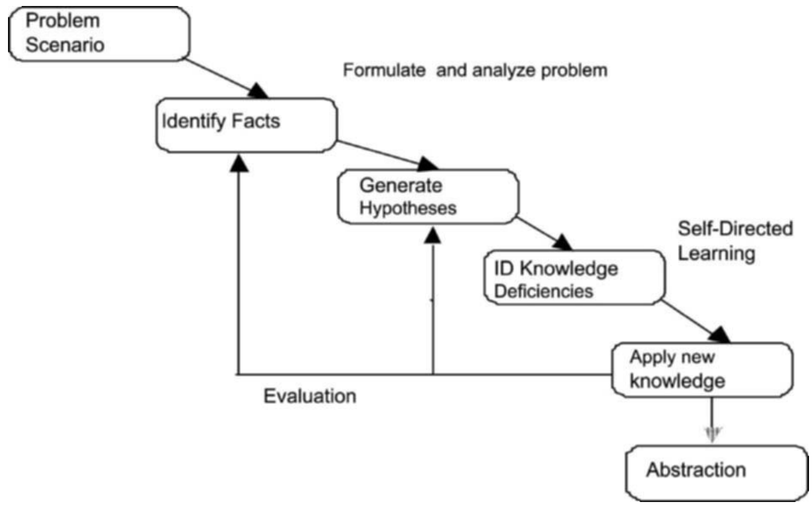

FIGURE. 1 The Tutorial cycle (reprinted with permission Hmelo-Silver[9]).

statement to solution entails close reading and interpretation of the scenario, formulation and analysis of the larger problem into a solvable problem and the synthesis of a great deal of information gathered and applied by the group towards a solution. The solution presentation gives students the opportunity to practice developing presentations on complex biomedical engineering content and to build the speaking skills necessary to present their work in a public forum. Over the term, every group member presents at least once. Further, each group gets to see how other groups have handled the same problem, which helps them understand how one problem can generate multiple answers, some better than others. Moreover, the presenters learn to field probing questions from an audience as a mechanism for getting feedback on their ideas. And finally, these presentations help to build group commitment and solidarity because they serve as a public articulation of the whole group's work. Being mindful of the feedback and questions generated by the presentations, each group follows up on the presentation by developing a technical document that lays out their solution. This document is a mechanism for students to develop technical and scientific writing skills and once again, every student over the term must act as one of the primary writers, although generally all students are involved in writing all reports.

The tutorial group repeats this problem transformation cycle as they solve three or four problems during the term. As should be evident, this problem cycle replicates the kinds of activities that graduate students and researchers undertake as part of a research cycle, which is perhaps the reason that undergraduates who conduct research often comment that the PBL group is just like being in a research lab group and that the lab meeting and the PBL tutorial are much the same. The repetitive cycles assist students in developing "habits of the mind"[10] or socio-cognitive competencies desired in biomedical engineers.

WHAT DO THE PROBLEMS LOOK LIKE AND HOW DO YOU COME UP WITH THEM?

PBL problems are formulated to present minimal information about a situation.[2] This minimalism promotes self-directed inquiry, which is fundamental to students developing effective and efficient research strategies. Further, problems are designed to be open-ended, ill structured and poorly constrained. Such features help students develop expert reasoning strategies, as the tutorial group repeatedly practices formulating, constraining and analyzing problems towards crafting logical and appropriate routes towards optimal solutions. Problem openness also allows each student in the tutorial group to identify areas of inquiry for which she/he is responsible to the group. If the problems are overly constrained or structured, possible areas of inquiry will be too restricted for authentic individual inquiry activities. Finally, PBL problems are designed to address timely topics in order to engage and motivate students while introducing them to current problems of disciplinary interest. And most importantly for BME, problems are designed to demand disciplinary integration.

Three sample problems from the undergraduate curriculum with commentary will serve to illustrate how problems can anchor various kinds of knowledge acquisition and skills development. It is important to note that students working on these problems are in their second or third semester of an undergraduate curriculum and this is their first course in the BME undergraduate course sequence. Just as importantly, the problem statement is *the only thing* given to the student team. All information needed to resolve the problem is discovered and imported into the group by the team members.

Problem One: Identifying Optimal Methods of Breast Cancer Screening

Over the past two decades, intensive research into all aspects of breast cancer has led to more refined technologies for detecting breast cancer and improving outcomes for patients during and after treatment. However, we still have far to go to significantly reduce the threat of breast cancer through early detection and more effective treatments. In the United States in 2004, over 215,000 women and 1500 men were diagnosed with breast cancer, and over 40,000 died from the disease. It is the most common cancer among women in each of five major population groups (White, black, Asian and Pacific Islanders, American Indians and Alaska Natives, and Hispanics) in the United States, and the second leading cause of cancer mortality for women in all major population groups with the exception of Hispanics, for whom it is ranked first.

Although routine mammograms for early detection of breast cancer are conducted widely in the United States, two Danish scientists have claimed that these tests are not effective in saving lives. Further, false positives in screening have led to emotional distress and financial burden. Your team has been selected by the American Association for Cancer Research (AACR) to investigate the current status of breast cancer screening, including the effectiveness of mammography. You are expected to identify and make recommendations regarding potential future screening strategies, which, relative to current strategies, improve sensitivity without sacrificing specificity.

One of the reasons to start a PBL curriculum with a problem like this is that it requires a great deal of inquiry on the part of the students. This inquiry can range from the mechanisms of cancer at the molecular level, to the physics behind X-ray imaging technologies, to the protocols involved in a mammography screening, to highly experimental research that has the potential to create new screening paradigms. The student group will have to track down a vaguely referenced article as well as define discipline-specific terms like *false positives, sensitivity* and *specificity*. They will not only have to identify the most promising strategies but, more problematically, recommend the best which means comparing and contrasting methods based on the given criteria of sensitivity and specificity as well as others developed within the group. The complexity of this problem requires all team members to be involved in the inquiry. So by problem finish, each student will have started the process of developing excellent inquiry strategies by undertaking self-directed learning towards problem resolution.

Problem Two: Determining the Accuracy of Medical Devices

Fever measurement has been regarded as a diagnostic tool in routine medical practice for over 130 years. However, body temperature measurements and their interpretation vary, depending on a number of factors. These include the type of thermometer, the measurement site, the age and sex of the subject, and circadian fluctuations in body temperature. One of the relatively newer techniques for detecting the presence of fever is through the measurement of ear temperature, Devices designed for these measurements are considered fast and easy to use, features particularly attractive for use on children. However, there have been numerous reports of concerns over the accuracy, reproducibility and repeatability of temperature measurements made with ear thermometers.

Your group is challenged to develop a hypothesis for identifying a factor, other than device malfunction or device design, which contributes to one of the ear thermometer's low performance characteristics (i.e., accuracy, reproducibility or repeatability). You will then develop an experimental design to test that hypothesis. Your hypothesis should be formed based on a thorough study of both the physiology behind body temperature measurements and the sensor technology employed in your device. Your experimental study, to be conducted with an ear thermometer provided to you by your facilitator, must be designed to use the number of human subjects necessary to produce statistically significant results.

This problem is the second to be used in an introductory PBL. While it also requires students to conduct inquiry towards understanding the problems associated with ear thermometers, the real challenge lies in the design of an experiment meant to test a hypothesis. The team has to use the literature to develop a testable hypothesis. Then they need to develop an experimental protocol for collecting data to either verify or disprove their hypothesis. They must also figure out how to set up the experiment so as to determine whether the results are statistically significant or not. Further, they need to determine what an appropriate sample size will be to achieve significance. And finally every team member has to individually become IRB certified and the group must get IRB approval before collecting any data. The potential learning outcomes of this problem are complimentary to those of the first in terms of inquiry skill development but different in having students grapple with the challenge of designing viable and rigorous experiments.

Problem Three: Genetic Testing and Workplace Discrimination

Complaint # 983596-A was filed by Dr John Smith of Twinsburg, OH, on May 12, 2003, to the Equal Employment Opportunity Commission. Dr Smith alleges that NanoTech Inc, a small biomedical company based in Cincinnati, OH, discriminated against him on the basis of his genetic profile. Partially because of intense public interest and media coverage, a Congressional committee is investigating this issue, and your team has been called in to testify before Congress as scientific experts on the topic.

The details are as follows: Dr Smith was let go 2 weeks after starting as the research director of clinical applications. These 2 weeks were within the 4-week probationary period made explicit during the interview process. The letter conveying this news to Dr Smith explicitly stated that he was being let go because genetic analysis on his saliva swab (done shortly after he joined the company) revealed that he had a susceptible serotonin transporter gene ('s/s genotype') that had been identified as responsible for increasing the probability that one might develop clinical depression or be non-responsive to anti-depressant therapy. At the time, Dr Smith had no episodes of depression in his medical history. However, the company stated that this result would significantly impact the company's insurance premiums.

Based on the most current research, you are to testify on the state of the science involved in predicting future disease, specifically depression and associated diseases. Importantly, your recommendations need to be mindful of a variety of stakeholders including individual citizens and employees, employers, insurance companies and society at large. Specifically, you need to address the following:

- *The protocols generally followed in genetic testing, their reliability and accuracy.*
- *Your recommendation to the Congressional committee from this specific case perspective on the validity of the science behind Nanotech's decision.*
- *Whether this is a valid case of risk-assessment, or whether it is akin to discrimination on the basis of race, gender or disability, which is explicitly forbidden by law. Effectively, should the Congress enact laws relating to genetic profiling?*

This very complex but timely problem brings science, ethics, social impacts and policy together in a realistic scenario. Once again it offers many obvious areas for inquiry—the state of genetic testing predicting depression, techniques of risk assessment, bioethical frameworks, and legal issues related to discrimination, to name a few. Most importantly however, students are given the chance to see how changing scientific knowledge, policy decisions and ethical behavior can come together to create a potentially troubling situation. The problem goal is to have them practice systematically analyzing the scientific information as a first step towards equitable and ethical policy decisions.

Problem development is an on-going activity within a PBL curriculum for a couple of reasons. First it is important to keep problems current so students are introduced to the latest technologies and so that they have a sense of working on authentic not spurious problems. Also facilitators can tire of the same problems every term so constantly developing new problems precludes this. There are several ways to devise problems.

1. Focus a problem on a specific content area such as transport that you want the students to master. This can be tricky because the problem needs to be constrained enough to focus student attention but open enough to afford individual inquiry and varied answers and routes to the solution.
2. Develop a problem that forces the group to practice a skill such as modeling or physical design.
3. Create a series of problems that focus on a topical area such as cancer but from different perspectives such as imaging or drug development.
4. Develop a problem that highlights a particular area of BME such as neuroengineering or biomechanics.

It is common for problems to undergo several iterations during development. This is because the wording of the problems and the deliverables need to be carefully crafted to insure that students focus on what is intended. In our program, one faculty member takes the lead in writing the first draft, which is circulated among other faculty for comments and changes to be incorporated into the problem statement. When acceptable wording and focus have been achieved, the problem is released to the PBL groups for first-time testing. Problem flaws identified during this piloting are addressed before rerunning the problem another time. The Georgia Tech database of BME problems can be accessed at http://www.bme.gatech.edu/pbl.

WHAT DOES THE FACILITATOR DO? HOW ARE THEY TRAINED? AND HOW DO YOU MANAGE THE INCREASING NUMBERS OF BME UNDERGRADUATE MAJORS?

A facilitator is very different from an instructor. She/he does not give information (act as an expert) or direct the group towards a solution (determine and guide a solution). Rather, the facilitator asks probing questions at the process level with the intent of explicitly revealing group behaviors by drawing attention to student actions.[1] These questions should model the kinds of internal monitoring and evaluation of one's actions and work that characterize more expert behavior. In this way, the facilitator/group interactions make explicit the cognitive behaviors that learners are being helped to develop. Example questions of various types from the facilitator might be:

> Where did you find this information and how reliable is it? So far, the group has generated only one possible solution, what are some other ideas people have been thinking about? Why don't you go to the board and try to draw a diagram of that complicated system you just tried to explain in words? Do you think the group members understood what you explained without giving them something to look at? That sounds like the beginning of a hypothesis. Can you make it into one? We have not heard from Ashley today. How does your research apply to the problem? Do you feel like you have exhausted all possibilities for research on this topic? Where else could you look?

Over time, as the facilitator moves more into the background or put another way, as the support fades, an experienced PBL team will ideally do this in-depth probing on their own—peer to peer, which is why this kind of guidance or support is called *scaffolding*. The initial support provided by the facilitator is slowly dismantled as the students develop greater proficiency. Facilitators do not need to be content experts or knowledgeable about each problem domain. In fact, being an expert in the problem area often makes it difficult to facilitate and not teach. It is the students who are expected to become the experts as they conduct research towards reaching a solution. Facilitators who try to master all of the material and intentionally prod the tutorial group towards a particular solution have failed to understand the role of the facilitator, which is to articulate the kinds of questions that students will learn to generate for themselves as they develop into complex problem solvers.

At the end of each problem cycle, one session is set aside for self, peer and group evaluation. Here the facilitator guides the students in orally reflecting back on their own work during the problem, the work of their peers and of the group as a whole. There are four specific topics for individual and group reflection: *inquiry, collaboration, knowledge acquisition and problem solving*. Orally, each student assesses his/her own inquiry activities, role and action as a member of a group, development of knowledge in the problem domain and increasing abilities to tackle complex, ill-structured problems. Others in the group respond to the self-critique giving feedback to that student. Problems in the group are aired and potential new modes of working and interacting are discussed. This session is critical to launching the group into the next problem. If group and individual difficulties are not discussed candidly, there is no possibility for change and for group learning. The facilitator plays a central role in helping individual members and the group as a whole define and articulate issues and frame future routes for positive change.

Perhaps the single major challenge to implementing such an educational approach is staffing multiple sections. In our program, as the undergraduate numbers grow to nearly 200 new students a year, the department has continued to devise ways to work with existing resources to allow all students to experience two semesters of this approach before graduating. Presently staffing is accomplished by using faculty members, postdoctoral researchers interested in building a teaching portfolio and PhD students who have experienced PBL themselves as learners. It is not uncommon for a faculty member to have two groups a semester, with whom they meet a total of six hours a week. New facilitators attend a three-hour training session in which the elements of PBL and their role in the process are discussed. They also receive a copy of *The Tutorial Process*,[1] a guide to the facilitation process developed by PBL experts at Southern Illinois School of Medicine. All facilitators meet once or twice a term to discuss how problems are going, which issues are arising in the groups and to receive tips on how to handle different kinds of situations. If anything, facilitators in the first term err on the side of too little prodding or questioning, fearing they might be teaching not facilitating. The very interesting thing is that many junior faculty find that facilitating PBL groups is very helpful in thinking about their own research lab groups and how they might be run. Often an interesting cross-fertilization of ideas across these two sites occurs.

HOW DO YOU DETERMINE A GRADE?

Assessment in our PBL classes targets four areas: *self-directed inquiry, knowledge building, collaboration skills* and *problem solving strategies*. However, other programs could easily determine other targets for assessment, targets that focus more on the acquisition of content knowledge in specific domains. We describe our target learning outcomes in terms of specific behaviors that can be observed and evaluated by the individual learner, his/her peers and the facilitator. Each behavior starts with a verb that indicates that the learner is doing something which can be evaluated from observing the student in interactions with the group. The expectation is for the learner to develop in each of these categories over the term, but we make it clear to the students that a single PBL course is only the start of a much longer process. In the final analysis, we believe that these skills are the building blocks of life-long learning and that the more they practice them in a supportive environment as undergraduates, the greater their progress. The assessed behaviors are shown in the table given below. Inquiry and knowledge building skills fall under one category because in observation it is very difficult to disentangle the two.

Self-directed inquiry/knowledge building	Problem-solving skills	Collaboration skills
Recognize the inadequacies of knowledge	Define the problem and its goals	Tutor group on your relevant inquiry findings
Identify learning needs and the next layer of information to be tackled	Explore the problem space searching for critical features and fundamental principles	Facilitate interaction with other members
Set specific learning objectives	Assess and use prior knowledge to solve problem	Stick to main themes without meaningless side tasks
Make a plan to address these objectives	Develop provisional hypotheses of how to solve it	Monitor group progress and give feedback
Evaluate your inquiry	Identify key new knowledge and skills needed to solve the problem	Complete tasks on time
Assess the reliability of sources	Plan and carry out a strategy of attack	Demonstrate enthusiasm and involvement
Evaluate how the sources contribute to knowledge	Situate new findings in previous understanding	Give emotional support to others
Utilize the problem to deepen knowledge in all problem areas	Apply new knowledge judiciously to solve the problem	Express disappointment or disagreement directly
		Avoid contributing excessive or irrelevant information
		Help group develop team goals and willingly forego personal goals for team goals

A variety of methods are used throughout the semester to collect data on how well students are progressing in the four target areas. Each has a different focal area. All are listed below.

- *Inquiry notebooks*—each student develops a notebook of all the research that s/he does for the problems. At a minimum it contains the inquiry undertaken, weekly summaries detailing the pertinent findings and research of other group members. Periodically, the student turns it in for assessment purposes. A scoring rubric is used both to assess the quality of the notebooks (inquiry) but also to guide students towards particular goals.
- *Post-problem self and peer evaluation*—This is described earlier.
- *Concept maps*—At the conclusion of a problem, each student develops a concept map that represents his/her knowledge of the problem domain.[13,19] These maps are graphical representations that depict the understanding and structure of knowledge that a student takes away from solving a complex problem. The map is used to assess the depth and complexity of the conceptual knowledge. The numbers of nodes (concepts) and the complexity of links are used as indicators of knowledge growth in the problem area.
- *Written and oral presentations*— Each student makes a formal problem solution presentation and participates in writing a final problem report. These are used to evaluate the progress the student is making in the areas of expression, organization, and clarity in oral and written formats. Scoring rubrics have also been developed for the presentations and reports. (See Appendix A for an example.) Again, specific behaviors are identified for both the students and the facilitators and scores are assigned using a scale consisting of *exceptional, proficient, apprentice* and *novice*. Using this scale is meant to signal to students that the development of presentation and writing skills is a process.
- *Mid-term facilitator meeting*—Every student meets with his/her facilitator mid-term for an individual evaluation session. The facilitator asks the student to first assess his/her development in a number of areas. Then she/he responds to the student assessment with his/her own assessment. This fosters a dialogue about the kinds of behaviors the student will need to demonstrate the rest of the semester.
- *Final written assessment*—At the end of the term, each student submits a written evaluation on each team member and his/herself. The document critically examines each person in the areas of *inquiry, knowledge building* and *collaboration*. Each group member is assigned a grade by the student evaluator.

Several discussions have been devoted to assigning a Pass or Fail at the end of the term which is philosophically more in line with helping students develop self-assessment skills. While the faculty are generally in favor of this, students are not, but this could be very different in another program.

ARE HYBRID COURSES THAT MIX PBL WITH TRADITIONAL LECTURES WORKABLE? CAN EVERY COURSE BENEFIT FROM A PBL APPROACH?

While courses that blend PBL with traditional lectures seem desirable because students can utilize lecture material in problem solving, in reality they are difficult to design and manage. This is because each instructional approach derives from a different model of learning. As described earlier, PBL embraces a constructivist model of learning in which students are empowered to identify and follow individual learning paths towards solving a problem. In contrast, a lecture format follows a transmission model of learning in which the expert/knower decides what needs to be learned and then tells or lectures the novice/learner. The first model implies an empowered learner who actively works to construct knowledge, the second a submissive learner who passively receives knowledge. When students are asked to engage in both kinds of learning in one class, students can have a difficult time embracing these contradictory roles. In fact, they may strongly resist in either direction.

Ideally for a hybrid course to be successful, the PBL model or problem should precede any lectures because it is best to first empower students in their own learning and then provide appropriate material in lecture format to boost the level of problem solution. Thus when designing such courses it is best to pose a problem for groups to tackle and solve with their own resources. Then use these solutions as a jumping off point for a series of lectures that contrast their solutions with more desirable ones which utilize reasoning strategies, tools or models that students either did not identify or did not have the background to pursue. This PBL/lectures sequence adheres to a just-in-time approach in which the context for learning has been established—the problem—and the lectures are experienced from the learner perspective as just another set of resources used in the problem solution.

CONCLUSION

Given that a problem-based learning naturally creates the need for learners to find and utilize resources from several disciplinary domains, it seems is an educational approach uniquely suited to the challenging field of biomedical engineering. Through tackling complex, open-ended problems repeatedly throughout the undergraduate years, students can develop the integrative thinking and problem solving that set BME experts apart from their single disciplinary peers. It prepares students to participate in research laboratories as undergraduates; it readies them for time-constrained problem solving in the real world and for graduate school. As one student recently observed, "PBL has pushed me in ways I could not imagine." This educational approach is well suited to the demands of a rapidly changing field that needs experts who can change and grow through life-long learning.

REFERENCES

1. Barrow, H. The Tutorial Process. Springfield, IL: Southern Illinois University Press, 1988.
2. Barrows, H. S. How to Design a Problem-Based Curriculum for the Preclinical Years. New York: Springer, 1985.
3. Barrows, H. S., and A. C. Kelso. Problem-Based Learning in Secondary Education and the Problem-Based Learning Institute. Springfield, IL: Problem-Based Learning Institute, 1995.
4. Barrows, H. S., and R. Tamblyn. Problem-based Learning: An Approach to Medical Education. Springfield, IL, Problem-Based Learning Institute, 1980.
5. Collins, A., and J. Hawkins, & S. Carver, A cognitive apprenticeship for disadvantaged students. In: Teaching Advanced Skills to At-risk Students, edited by B. Means, C. Chelemer, and M. Knapp. San Francisco, CA: Jossey-Bass, 1991.
6. Duch, B. J., S. E. Groh, & D. E. Allen, The Power of Problem-based Learning: A Practical "How to" for Teaching Undergraduate Courses in Any Discipline. Sterling, VA: Stylus, 2001.
7. Fink, F. K. *Integration of engineering practice into curriculum-25 years of experience with problem based learning*. Frontiers in Education Conference, 1999. FIE '99. 29th Annual, San Juan, Puerto Rico, IEEE, 1999.
8. Hmelo, C. E. Problem-based learning: Effects on the early acquisition of cognitive skill in medicine. *J. Learn. Sci.* 7:173–208, 1998.
9. Hmelo-Silver, C. E. Problem-based learning: What and how do students learn? *Educ. Psychol. Rev.* 16:235–266, 2004.
10. Keating, D.. Habits of the mind for a learning society. In: The Handbook of Education and Human Development, edited by D. R. Olson and N. Torrance. Oxford, UK: Blackwell, 1996.
11. Lee, V. S., Ed. Teaching and Learning through Inquiry: A Guidebook for Institutions and Instructors. Sterling, VA: Stylus, 2004.
12. Newstetter, W. Creating cognitive apprenticeships in biomedical engineering. *J. Eng. Educ.* 94:207–213, 2004.
13. Novak, J. D. Learning, Creating and Using Knowledge: Concept Maps as Facilitative Tools in Schools and Corporations. Mahwah, NJ: Erlbaum, 1998.
14. Patel, V. L., G. J. Groen, & G. R. Norman, Effects of conventional and problem-based medical curricula on problem solving. *Acad. Med.* 66:380–389, 1991.
15. Patel, V. L., G. J. Groen, & G. R. Norman, Reasoning and instruction in medical curricula. *Cogn. Instruct.* 10:335–378, 1993.
16. Perrenet, J. C., P. A. J. Bouhuijs, & J. G. M. M. Smits, The suitability of problem-based learning for engineering education: Theory and practice. *Teach. Higher Educ.* 5(3):345–358, 2000.
17. Said, S. M., M. A. Adikan, S. Mekhilef, & N. A. Rahim, Implementatiion of the problem-based learning approach in the Department of Electricl Engineering, Univerity of Malaya. *Eur. J. Eng. Educ.* 30:129–136, 2005.
18. Smith, K. A., S. D. Sheppard, D. W. Johnson, & R. T. Johnson, Pedagogies of engagement: Classroom-based practices. *J. Eng. Educ.* 94(1):87–102, 2005.

[19.] Walker, J. M. T., K. Paul, & D. Corday, The use of Concept Mapping as an Alternative form of Instruction and Assessment in a Capstone Biomedical Engineering Design Course. ASEE, Nashville, TN: American Society for Engineering Education, 2003.

[20.] Woods, D. R. Problem-based learning for large groups in chemical engineering. In: Bringing Problem-Based Learning to Higher Education, edited by L. A. Wilkerson and W. H. Gijselaers. San Francisco, CA: Jossey-Bass, 1996.