Int. J. Engng Ed. Vol. 23, No. 3, pp. 483–490, 2007
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Student-driven Learning in Integrated Lecture-lab Classroom Environments: The Role of Mobile Computing*

MIA K. MARKEY
Biomedical Engineering, College of Engineering, The University of Texas at Austin, Austin TX 78712, USA. E-mail: mia.markey@mail.utexas.edu

ARCHIE HOLMES JR.
Electrical and Computer Engineering, College of Engineering, The University of Virginia Charlottesville, VA 22904, USA. E-mail: ah7sj@virginia.edu

THOMAS F. EDGAR
Chemical Engineering,College of Engineering, The University of Texas at Austin, Austin TX 78713, USA. E-mail: edgar@mail.utexas.edu

KATHY J. SCHMIDT
Faculty Innovation Center, College of Engineering, The University of Texas at Austin, Austin Tx 78712, USA. E-mail: k.schmidt@mail.utexas.edu

This paper presents a critical overview of our experiences in using mobile computing for supporting both faculty and students in integrated lecture–lab classroom environments. Three case studies describe how handhelds, laptop carts, tablet PCs, and student-owned laptops/tablets can enable adaptive, active, applied learning. We identify the remaining challenges to be overcome before the potential of mobile computing can be fully realized. Some of those challenges are specific to mobile computing; however, many others are broader problems in engineering education, such as the need for involvement beyond the primary instructors (e.g., technical staff) and modern classroom facilities.

Keywords: mobile computing; integrated classroom; technology literacy

INTRODUCTION

WHILE THERE ARE MANY engineering classes in which a professor gives a traditional lecture, i.e., an oral presentation of the material with work done on the board while students dutifully take notes, this method of instruction is not the only model. Given that our minds become more engaged when we do more than listen, classrooms are shifting to learner-centered environments. The phrase, learner-centered, is a catch all term, and as such it can be misunderstood. Research suggests that for students to be actively learning they need to be doing more than just listening and taking notes; instead they need to be dynamically engaged in tasks and in thinking processes [1]. Active learning refers to the need for students to control their learning [2] and to facilitate consequent performance [3].

We use the phrase "integrated lecture–lab environment" to refer to a classroom environment in which the instructor cycles between presenting information and using instructional technologies to engage students in hands-on activities. As an example, consider a class session on the impact of operating variables in a distillation column in a separations course. The lecturer presents the concepts followed by demonstration of the equations and simulation results, perhaps augmented by McCabe–Thiele plots. The students then immediately prepare examples, following the presented directions using appropriate computer software. The instructional cycle may be repeated several times in a given lecture. This interactive mode of intermingled lecture and laboratory has a very high learning reinforcement value since the computer system mediates the rate at which information is presented to each individual student.

Note that the lecturer is not removed and instead is integral to the teaching process. While the laboratory exercises are going on, the lecturer can move among the students, looking over their shoulders and serving as an advisor and facilitator. Teaching and learning becomes more a one-on-one or small-group exercise and less of a non-interactive lecture experience. The instructor is transformed from being a "sage on a stage" to a "guide on the side." This integrated lecture/laboratory

* Accepted 18 March 2007.

mode of instruction is now being used in industrial training, particularly in the software industry where the need for on-demand learning is prevalent. With the advent of new digital technologies that allow for personalized learning, both industry and higher education are viewing learning as situated, collaborative, and ubiquitous.

Mobile computing is a natural fit for the integrated lab–lecture paradigm. The instructor can more readily switch the students' focus of attention between the lecture and lab modes when the lab equipment can be physically set aside except when needed. Larger class sizes can be accommodated with a mobile computing strategy since it enables any classroom, even a large lecture hall, to support a lab component. Similarly, mobile computing tools can enable the instructor to move about freely in a large class setting, facilitating more one-on-one interaction.

The purpose of this paper is to present a critical overview of our experiences in using mobile computing for supporting both faculty and students in integrated lecture–lab classroom environments. While there are many challenges in this process, we have found that it is helpful to organize the instructional issues along three basic concerns that motivate the use of integrated lecture–lab classroom environments. To begin with, one question is how to actively engage students in the learning process. A second pedagogical concern is how to create a flexible engineering educational delivery to support student-driven learning individually or in groups, in classrooms or non-classroom facilities, and at variable paces. Finally there is a need to strengthen the connection between coursework and applications in the "the real world." While these issues are not intended to be comprehensive, they provide a framework for our experiences in addressing curriculum changes with mobile technologies. In this paper we offer three case studies on how handhelds, laptop carts, tablet PCs, and student-owned laptops/tablets can enable adaptive, active, applied learning.

CASE STUDIES

How to actively engage students in the learning process

The goal of Chemical Engineering at The University of Texas at Austin (UT Austin) is to aid in the intelligent use of the bountiful natural resources in Texas. As of 2005, the undergraduate enrollment in Chemical Engineering is approximately 500. The Chemical Engineering Department makes heavy use of computing by presenting it in an integrated fashion so that the student's capabilities grow during their undergraduate years. The software used includes Excel® (Microsoft Corporation, Redmond, WA), MATLAB® (The MathWorks, Natick, MA), JMP® (SAS Institute, Cary, NC), the computational fluid dynamics package FlowLab® (Fluent Inc., Lebanon, NH), and Aspen Plus® (Aspen Technology, Inc., Cambridge, MA), which is used for flowsheet simulation of chemical plants. Currently these software tools are used in eight required courses. Class sizes in these courses range from 20 to 90 students. With classes this size, mobile computing provides the most practical strategy for including hands-on software experience in class sessions.

A generous grant from Advance Micro Devices, Inc. (Sunnyvale, CA), coordinated by Dr. Edgar, allowed the Department to obtain 40 laptop computers to enhance instruction. These laptops, which comprise the mobile classroom system, are kept in two carts and handed out in each class when computer-based materials are covered. The purchase of 40 laptops allows a ratio of two to three students per computer (team problem-solving) in our larger classes.

Given that these laptops were introduced to engage students in their learning, we need to provide an operational definition of engagement. Numerous factors, such as time (length of class or time of day), space (arrangement of furniture and layout of room), materials (readily available and easily accessible), and relationships (teacher's personality and teaching style) all influence student engagement in their learning. At its basic level, student engagement is when students are involved in the instructional process. Keeping students interested and motivated to learn is not solely the responsibility of a professor for there are many factors that contribute to a student's level of engagement in learning [4]. There is research, however, that suggests there are instructional strategies and methods to promote student interest and engagement [5] and we are finding that mobility can facilitate engaging students by enabling active learning, providing prompt feedback, and encouraging cooperation among students.

We have observed that with mobile technologies our students are talking more and interacting with each other as well as with the computing devices. Our anecdotal assessment is finding that wireless laptops for students are well-received because laptops allow students to work through the tutorials at their own pace and yet professors and teaching assistants are able to guide them through the more complicated points in the software usage. We relate a few quotes here as examples of the type of qualitative feedback we have received from our students. John Hedengren, graduate student and a teaching assistant for the process control class said, "The laptops were a valuable asset. Most of the students were able to get a quick working knowledge of MATLAB/Simulink in less than an hour of in-class demonstration." Another student, Jonathan Richter, who graduated with his BS ChE degree in December, 2003, provided the following comments: "I have had experience taking classes which used other computer labs as well as experience with the new laptop computers for in-class tutorials. The laptops are far superior. First, with the laptops everyone is facing the front of the class with a clear view of a projection of the TA's screen. In the computer lab, the students may or may not be able to see what the TA is doing, a huge impediment to the ease of learning. Second, other computer labs require a new log-in account, which I know from personal experience is not always reliable."

While such comments are insightful, their qualitative nature limits our ability to paint a full picture on the issues of using mobility for instructional enhancements. There are predictions that mobile technologies are the next step in technology-mediated learning [6], but empirical evidence that supports mobility's instructional impact and efficacy is limited. Currently, we are developing surveys to get insights into the cognitive, pedagogical, and social aspects of mobile learning and discussing developing usage logs and observational protocols. We plan on continuing to monitor the literature to see the influences of these technologies. Our question is how do laptops and mobility result in increased learning, greater participation, higher learning motivation and pressure to perform in the classroom? A summary of lessons learned and ongoing challenges, both technical and instructional, is discussed at the end of this paper.

How to create a flexile, adaptive engineering educational delivery

As UT Austin's largest engineering department, the Electrical and Computing Engineering Department (ECE), has 62 full-time faculty and 21 part-time faculty working with approximately 1400 undergraduate students. The large size of the department makes it challenging to tailor the educational experience for individual students.

We have collected information on student learning styles (using the Index of Learning Styles [7]) in two of Dr. Holmes' undergraduate courses since 1999. One is focused on DC linear circuits and is a required first-year ECE course and the other is a course on semiconductor devices, which is required and taken by juniors and seniors. Over 500 students have been surveyed in these courses. While the results vary by semester and course, some important trends have emerged.

- The typical UT ECE student has no preference between the global and sequential learning styles.
- The typical UT ECE student has no preference between the intuitive and sensing learning styles.
- The typical UT ECE student has a *slight* preference for the active learning over reflective learning.
- Most UT ECE students have a *strong* preference for visual learning over verbal learning.

Thus, it is important that UT ECE faculty investigate ways to enhance the visual delivery of course content. Mobile computing is one strategy that can be employed to help shift the balance of the classroom experience from a more verbal presentation to a more visual presentation.

We have found that students in the required freshman introductory electrical engineering class (which covers DC linear circuits) come into the course with a wide range of previous experiences; this presents another challenge. Some students have had exposure to these concepts via a calculusbased physics class in high school or have participated in hobbies, which used these circuit elements. Other students are just beginning calculus for the first time at the University. Others had a physics course in high school that did not emphasize DC circuits.

Given the variation in students' backgrounds, another goal of introducing mobile computing was to "help both the students and instructor access what is understood by students in real-time in the classroom" [8]. We had experimented with some success the use of peer instruction [9] during lectures, but we wanted a means that provided real-time feedback to an instructor about students' understanding. With this information, the instructor could intervene, as needed, to help students master important course concepts.

In the fall of 2001 with the generous support of a mobile technology grant from Hewlett Packard Company (Palo Alto, CA), coordinated by Dr. Holmes, students were introduced to an early product of hand-held PCs, the Jornada. Several times during the semester, students used their Jornadas to take quizzes offered through Prometheus (a course management system that has since been purchased by BlackBoard Inc, Washington, DC). The results were fed to the instructor so that he could gauge their collective comprehension levels during class time (this system also allowed the instructor to view individual student comprehension—that feature was not used during this initial test). Armed with knowledge of their understanding, the professor could adjust class time to meet the needs of the students. For example, let's say that the professor had three main topics that he planned to cover in lectures that day. A quiz can be used to gauge student knowledge of these three topics. While the instructor may have planned to cover these topics equally, the quiz may reveal that the students really grasp the first two topics and are struggling with the third. As a result, the instructor can adjust lecture time to briefly cover the first two topics and spend more time where it is needed—on the third topic.

While the early generation Jornadas were not ideal, they were a first step in exploring how to create a flexible instructional environment. The results of this pilot test did show two important things. First, students need to be held responsible (via an effect on their course grade) for attempting to learn the material before coming to class. The quizzes given at the beginning of class need not be complex; they just have to ensure that they can assess if the students have spent time preparing. Second, students have varying needs when it comes to assessment. Many students wanted problems that did more than measure whether they "learned" the material. They wanted to be challenged to see how well they understood the material. This need requires an exam platform were there are easy and hard problems. One promising approach is adaptive testing where a standard testing bank is used to build a custom exam for each student.

The approach for adaptive testing works as follows. All students start with the same question. If the question is answered correctly, a more difficult question is provided; if the question is answered incorrectly, a question of similar difficulty is asked. As students continue to answer questions correctly, a more difficult question is asked until the student meets the expectation of the instructor. When more than one question is missed in a row, the student goes to a more basic problem to build their skills up. In the end, the goal of adaptive learning is to get each student to the same level of mastery regardless of how many questions are needed.

While this adaptive learning approach is highly appropriate for out-of-class assignments, it can also be used in the classroom by providing the instructor with the level of question answered by the students and their collective success rate. This way, the instructor can either allow the students to keep working or step in to provide appropriate instruction via lecture or additional classroom activities.

How to strengthen the connection between coursework and applications in the "the real world"

The Department of Biomedical Engineering (BME) at UT Austin was formed in 2001 and enrolled its first undergraduate students in Fall of 2002. BME is one of the smallest departments in the College of Engineering, with a total enrollment of approximately 430 as of Fall 2005, the first semester in which four classes of students were enrolled. Anecdotal reports suggest that the BME major attracts students to engineering who would otherwise have elected for a major in the natural sciences, particularly in the biological sciences. It is not unreasonable to suppose that on average students in BME at our institution may be less familiar with mobile computing technologies than students in some other majors such as ECE.

This case study concerns the use of computational labs to help students appreciate the role of probability and statistics in real BME applications. We have experimented with mobile computing to achieve this goal in both undergraduate and graduate courses [10]. A mobile computing approach based on a "mobile classroom" laptop-cart model was adopted because it was thought that this would allow for greater flexibility in the number of students that could work collaboratively. Collaborative efforts enable students to self-sort based on comfort-level and can be a step towards adaptive learning.

The enrollment in the undergraduate probability and statistics course is normally (50–70 students), and there is a dedicated weekly "lab session" for computational exercises. The weekly labs are lead by a graduate teaching assistant working in close collaboration with the lead instructor. In the graduate course, we initially tried moving back and forth between lecture and active learning computer exercises in the same class session. In response to student feedback, however, we have since adopted a model in which the mobile cart system is used only for a few designated "lab days" in the graduate course.

Quantitative items and qualitative comments on the end-of-course undergraduate student surveys indicate that the computational labs do help the students better appreciate the "real world" applications of the material. However, two inter-related issues with the lab sessions have also been identified. One was that some students find the labs to be difficult if they lack previous experience with the programming language used (MATLAB®, The MathWorks, Natick, MA). The other is that technical problems with the laptop-cart system can be very distracting. Examples of the technical problems we have had are laptops being completely uncharged or low charge batteries that did not last the entire session, very slow boot time, and inability to connect to the wireless network. Moreover, students tend to conflate the two issues, i.e., comments indicated a tendency to blame the laptop for their difficulties in using MATLAB® and vice versa. Consequently, we have added more background material on working with MATLAB® and switched to using a traditional "non-mobile" computer lab to lessen the technical difficulties. The undergraduate end-of-course surveys continue to show that the computational labs are valuable and help students apply what they learn in the course. The slower introduction to MATLAB® also seems to have cut down on concerns in using that tool. The positive transition from laptops to desktops made it apparent that the potential of mobile computing was not realized in the undergraduate probability course. There are probably a variety of reasons for this failure, but chief among them is presumably the students' frustration in working with an early-generation technology. For example, there was little discussion of who would collaborate with whom, beyond, "Can anyone get a laptop to work?"

The same laptop-cart system was used with the graduate course as in the undergraduate course and similar difficulties were experienced. On average, our graduate students are less frustrated by technical setbacks. The graduate students, however, are also more easily derailed by the temptation to try to fix the computer problems to the detriment of paying attention to the course material. Since the laptops have to be booted at the beginning of the session to make sure they are ready when needed and no student wants to part with a laptop that they manage to get working, the students and instructor essentially have to contend with the distractions inherent to a class held in a computer lab. Thus, the goal of seamlessly moving back and forth between lecture and computer exercises was not realized.

Owing to the particular room in which the graduate course was unfortunately scheduled one semester, important lessons were also learned on the impact of infrastructure on the success of mobile computing in engineering education. One problem was that the network access point nearest the classroom was overwhelmed by having 20–25 laptops all trying to connect at the same time. This was effectively resolved by working with our College Information Technology unit, but such problems cannot be solved overnight. Thus, there were some distracting and frustrating days for the students in the interlude. The tiny desks provided in the classroom made it nearly impossible for students to actually switch back and forth between using the laptop and other course materials such as their textbook. Moreover since the desks were bolted to the floor, our "mobile computing" laptops were immobile in practice.

We continue to use the laptop-cart system in the graduate course for designated "lab days," due in large part because the mobile system enables almost any classroom to be used, which is critical since there is high demand for the computer lab classrooms on our campus. We have also observed that the laptop-cart system allows the students more flexibility in who works together on the labs, which we consider quite positive. Moreover, a major drawback to traditional "non-mobile" computer labs is that the stations are often situated such that some students are forced to face away from the location of the projection screen or whiteboard that the instructor may want to use to communicate information to the class. This is distracting to both the instructor and students, as discussed in the first case study above.

With the transition to the non-mobile computer lab for the undergraduate course, the question arose as to whether mobile computing used by the *instructor* could enhance student learning. In particular, the students have expressed concerns that they struggle to compete for the teaching assistant's time even with a small class size and the teaching assistants indicate that they walk around the room answering the same questions repeatedly. Recently, we experimented with equipping the teaching assistants with tablet PCs (Motion Computing, Inc, Austin, TX) and a wireless projector. The idea was that this arrangement would enable the teaching assistants to walk around the room and answer individual questions, yet quickly display an answer to the entire class if they encountered a common question. The main limitation we found to this strategy was that the teaching assistants reported that it was very awkward to write "code" using the stylus since they were used to programming by typing. Professor Markey has also used a tablet PC for lecturing. However, since most of our classrooms are not equipped with a wireless projector, the experience thus far has not been substantively different from using the desktop machines provided in the classrooms. There is considerable potential to make student–instructor interactions more flexible through mobile computing and we will continue to explore the role for both student and instructor laptop/tablet computers.

LESSONS LEARNED

Remaining challenges

While mobile computing has high potential for enhancing student learning, we identified several challenges based on experiences thus far that remain to be overcome. Perhaps the biggest challenge with using any technology, including mobile computing technologies to support communication in an educational setting is that they introduce a new set of distracters for students. For example, we observed many instances of students using laptops to check their email, surf the Web, and work on homework for other courses, etc., during class time instead of working on course learning activities or listening to directions from an instructor. It is true that students have always been able to "tune out" what is happening in a class by sleeping, day dreaming, doodling, and so on. Such old school avoidance activities, however, do not carry with them the same element of plausible deniability as access to "information services" such as the Web. We suspect that many students honestly believe that this access to information from outside the classroom during class time does not hinder their learning. On the contrary, as discussed in a recent issue of ASEE PRISM [11] one recent study reports that "over-juggling" of electronic information lowers IQ scores more than losing a night's sleep or smoking marijuana!

The temptation to "play tech support" is another potential distraction that we noted in our ventures with mobile technologies in engineering education. All technologies have some failure rate and not surprisingly newer devices/software such as some mobile computing tools tend to have more "bugs" needing immediate attention. Engineering students may be particularly prone to disengagement from the course content by having their attention drawn to trying to "fix" some aspect of a technology used in the class.

Even when mobile computing technologies work as intended and students stay on task as intended, the learning curve associated with their introduction can be problematic. It is important to recognize that there is a learning curve for both instructors (faculty and teaching assistants) and students. In our experience, we noted that students and instructors can interpret learning curve issues differently in unexpected ways. For example, students who are unfamiliar with a particular software package may blame the laptop running the software for their frustrations rather than their lack of expertise. As one would expect, we have also observed that students are much more open to the introduction of new instructional technologies, mobile or otherwise, when they feel that their concerns about working with the new tool and software are respected and care is being given to help them become proficient.

While many engineering students may be comfortable enough with mobile computing to become distracted by opportunities to "debug", others may be unfamiliar with the tools adopted for course use and may have some anxiety as a consequence. Based on our experiences, we suspect that the proportion of students who are very concerned by the introduction of new technologies in class varies across the engineering disciplines and with the specific technology under consideration. Thus, when mobile computing is to be used in an educational setting, it may be particularly important to gauge students' knowledge and assumptions entering the course. Higher education has not lead the way when it comes to assessing students' entry or prerequisite knowledge and skills and yet if we continue to make assumptions that students either already know how to use technology or will learn it on their own concurrently with their studies, we will continue to find significant gaps in student capabilities. Advances in learning sciences are highlighting the need for instructors to identify and work with students preexisting understandings [3] and we are finding that if this core learning principle is overlooked when it comes to integrating mobile technologies into engineering classes, the consequences are diminished learning and high levels of student frustration.

The advent of mobile computing in engineering education goes beyond classroom instruction because it raises new issues pertaining to recruitment and retention. We need to take care that students from less affluent backgrounds are not inadvertently disadvantaged by assumptions about students' prior experience with mobile technologies. Another issue in recruitment and retention concerns the changes to classroom dynamics that can result from introducing mobile computing. Our observations suggest that using technologies such as laptops during class sessions may at least temporarily transform the environment from more lecture-like to more lab-like. While there are many positives to that transformation, it should be noted that group dynamics are different in lecture and lab settings and this should be taken into account in planning course activities with mobile computing devices.

The startup costs of introducing mobile computing into engineering education must be carefully considered before a new tool is adopted. One should keep in mind that there are costs in terms of many different kinds of resources (money, space, time, IT support, student goodwill, etc.) and that those costs vary with different technology options. Naturally, there is a tendency to focus on the upfront monetary costs. We emphasize, however, that on-going costs for upgrades and technical support must be taken into account if any technology, mobile or otherwise, is to positively impact student learning. We cannot overstate how critical effective technical support from the College was to our ability to introduce mobile computing technologies into our classrooms. Moreover, the effective deployment of technology in the classroom is facilitated by interaction with education and learning scientists, such as through our Faculty Innovation Center. While our own experiences were largely positive, we emphasize these points as potential negatives in recognition of the fact that institutional support for such resources can very widely.

In planning the purchase of any technology to be used in an educational setting, one must be concerned about anticipating future changes to the technology. This is a particularly sensitive issue with mobile computing technologies since many are early in their development cycles. Based on our experience, we recommend caution with regard to widespread, quick adoption of an early version of any new system. If problems are encountered, student and faculty support can be eroded and potentially inhibit the later adoption of more reliable second or third generation tools. It is valuable to work with a small group of "early adopters" on the faculty who are willing to accept the occasional failure when exploring new avenues for mobile computing in the curriculum. Similarly, one should carefully consider the student group that would be likewise involved in the testing of a new system. For example, it may be more practical to test a new use of mobile computing in a small course section first.

Finally, the integration of new technologies depends on broad infrastructure issues such as classroom design and availability. While we still have many auditorium-style, fixed-seating classrooms that limit student and faculty movement and are also not designed for student use of technology at our institution, we are conscientiously redesigning our learning spaces to be more appropriate for today's interactive technology enhanced teaching. We suspect that the challenges of such legacy classrooms are not unique to our situation.

Initial successes

Despite the challenges faced in integrating mobile computing into engineering education, we feel that the successes of our initial experiments in this regard are extremely encouraging. In our experience, the most important instructional role of mobile computing is to enhance student engagement. Mobile computing technologies enabled us to develop integrated lecture–lab environments that were truly learner-centered with an emphasis on active learning. In *any* active learning situation there is an element of fear of impending chaos because the instructor must yield some control to the students. Underlying many of the challenges of integrating mobile computing are broader pedagogical issues that are *not* specific to the technology but must inevitably be faced in order to move beyond the traditional lecture format. For example, in our experience, the distractions faced by students using mobile computing are notably different from those engaged in other active learning exercises (e.g., peer tutoring), but not more numerous. In our opinion, needing to help active students stay on task is a big step up from needing to get students actively engaged at all.

A significant advantage of computing-based over non-computing active learning is that it provides the opportunity to promote technology literacy. Especially for engineering education, our classrooms should reflect real problems and real problem-solving strategies. Much of the real-world engineering workplace revolves around a computing infrastructure. Moreover, helping students see the application of course material outside the classroom motivates them to be more engaged in the classroom. We have found this to be especially critical for subjects that students do not enter with enthusiasm, such as statistics.

Another favorable element to computing-based strategies is that they make it more practical to probe students' understanding at higher levels of thinking as identified with Bloom's taxonomy [12] than could otherwise be done during a class session. Solving many engineering problems is prohibitively slow or even impossible without sophisticated software. Thus, active learning exercises that employ engineering software enable our students to spend more class time on analysis, synthesis, and evaluation processes. For example, we observed that introducing a computational element to our probability and statistics course allowed the instructor to develop activities that targeted higher levels of Bloom's taxonomy [10]. Thus, computing-based activities in engineering education can make more efficient use of students' time and avoid frustrating students with calculations that can seem like "grunt" or "busy" work.

Mobile computing is more beneficial than non-mobile computing because it enables the instructor to integrate active, applied lab-like learning opportunities into a lecture environment. Mobile computing allows the instructor to convey information broadly to the class through a lecture-style presentation and then, in the same facility and time slot, switch to engaging the students in computationally-intensive active learning exercises. While we found that the seamlessness of the transition depends heavily on the robustness of the particular mobile computing platform and the flexibility of the classroom design, the benefit of mobile over non-mobile computing was still apparent in our initial tests.

CONCLUSIONS

The potential for mobile computing to support student-driven learning in integrated lecture–lab environments is tremendous. Our experiences as illustrated in these case studies have produced more positives than negatives. While we have yet to fully realize this potential, we believe that mobile computing can enable instructors to transform the classroom to provide active, adaptive, and applied learning opportunities. Many challenges, however, remain to be overcome before these goals can be practically reached. While some of those challenges are specific to mobile computing, many others are broader problems in engineering education, such as the need for involvement beyond the primary instructors (e.g., technical staff) and modern classroom facilities.

It is feasible to recommend that not only professors but also students will need to approach classrooms with a different mind frame. Enabling access to the world outside the classroom is a strength of many mobile computing technologies, yet we must consider whether technological limits need to be placed on that access and/or if our students need new guidance on how to learn effectively in such an "open" environment. Students need to be willing to come to class prepared and able to disregard technological distracters in order to make the most of ubiquitous technologies. Professors will need to be willing to experiment with their instructional palettes for in-class as well as out-of-class learning.

While it is too early in our experience with mobile computing to have quantitative data on its impact on recruitment and retention, we are optimistic that it will play a positive role. A widespread problem in retention of engineering undergraduates is that student can become disengaged from engineering due to the often very abstract nature of their initial coursework. Our positive experiences with mobile computing for promoting active, applied learning suggests it could be a valuable part of our wider strategy to introduce students to "real engineering" from the very beginning of the curriculum. Mobile computing also has high potential for supporting adaptive learning in which students can be supported in learning at different paces starting from different levels of preparedness. Widespread use of adaptive learning strategies would make it more practical for students from a broader spectrum of backgrounds to enter engineering and to succeed in our programs.

REFERENCES

1. C. Bonwell and J. Eison, Active learning: Creating excitement in the classroom. *ERIC Digest*, 1991091, 1991.
2. J. D Bransford, A. L Brown and R.R. Cocking, (Eds), *How People Learn: Brain, mind, Experience, and School.* National Academy Press, Washington, DC, (2000).
3. D. Lake, Active learning: Student performance and perceptions compared with lecture, in J. A. Chambers (Ed.), *Selected Papers from the 11th International Conference on College Teaching and Learning,* Florida Community College at Jacksonville, Jacksonville, April 2000.
4. L. S. Lumsden, Student motivation to learn, *ERIC Digest,* 370200, 1994.
5. A. Chickering and Z. Gamson, *Applying the Seven Principles for Good Practice in Undergraduate Education*, Jossey-Bass, San Francisco, CA, (1991).
6. E. D. Wagner, Enabling mobile learning' *Educause Review,* **40**(3), 2005, pp. 40–42, 44, 46–52.
7. R. M. Felder and L. K. Silverman, The index of learning styles, http://www.ncsu.edu/felder-public/ILSpage (2006).
8. A. Holmes Jr. and K. J. Schmidt, Do mobile and wireless technologies add value to higher education? *Proceedings from the 32nd Annual Frontiers in Education Conference*, Boston, MA, November 6–9, 2002.
9. S. Ramaswamy, I. Harris, and U. Tschimer, Student peer teaching: An innovative approach to teaching in science and engineering education, *Journal of Science Education and Technology,* **10**(2), 2001, pp. 165–171.
10. M. K. Markey, and K. J. Schmidt, An instructional technology scaffold for biomedical engineering statistics. *Proceedings from the Annual American Society of Engineering Education Conference*, Portland, OR, June 12-15, (2005).
11. T. K. Grose, Time to hang up? *PRISM*, **15**(3), 2005, p. 15.
12. B. S. Bloom, M. D. Engelhart, E. J. Furst, W. H. Hill and D. R. Krathwohl, *Taxonomy of education objectives: Cognitive domain*, Longman, New York, (1956).

Mia K. Markey is an Assistant Professor in Biomedical Engineering at The University of Texas at Austin. The mission of her Biomedical Informatics Lab is to design cost-effective computational medical decision aids that will help physicians better diagnose, treat, and manage cancer. Her primary interest in improving engineering education is the identification of effective strategies for coordinating instructional technologies to reinforce learning.

Archie Holmes Jr. Recently a Associate Professor in The Department of Electrical and Computer Engineering at The University of Texas at Austin. His technical research focuses on the development of optoelectronic devices for applications such as single photon counting and infrared imaging. His educational research interests include getting reliable, realtime feedback on student learning in the classroom and developing instructional materials that address diverse learning styles amongst engineering students. He joined the faculty of The Charles L. Brown Department of Electrical and Computer Engineering at The University of Virginia as a full professor in January 2007.

Thomas F. Edgar is a Professor of Chemical Engineering at The University of Texas at Austin and holds the George T. and Gladys Abell Chair in Engineering. Dr. Edgar received his B.S. degree in chemical engineering from the University of Kansas and a Ph.D. from Princeton University. For the past 35 years, he has concentrated his academic work in process modeling, control, and optimization, with over 200 articles and book chapters. Edgar has co-authored leading textbooks: *Optimization of Chemical Processes* (McGraw-Hill, 2001) and *Process Dynamics and Control* (Wiley, 2004). He has received major awards from AIChE (Colburn, Computing in Chemical Engineering, Lewis) and ASEE (Chemical Engineering Division, Westinghouse, and Meriam-Wiley). Recently he has carried out modeling and control research projects jointly with AMD, Motorola, Texas Instruments, Yield Dynamics, Tokyo Electron and SEMATECH, involving 15 Ph.D. students who now work in the microelectronics industry.

Kathy J. Schmidt is the Director of the Faculty Innovation Center for the College of Engineering at The University of Texas at Austin. In this position, she promotes the College of Engineering's commitment to finding ways to enrich teaching and learning. She works in all aspects of education including design and development, faculty training, learner support, and evaluation.