ADOPTION OF ACTIVE LEARNING IN A LECTURE-BASED ENGINEERING CLASS

Steven R. Hall[1], *Ian Waitz*[2], *Doris R. Brodeur*[3], *Diane H. Soderholm*[4], *and Reem Nasr*[5]

Abstract *— Three years ago, the Department of Aeronautics and Astronautics at MIT expanded its repertoire of active learning strategies and assessment tools with the introduction of muddiest-point-in-the-lecture cards, electronic response systems, concept tests, peer coaching, course web pages, and web-based course evaluations. This paper focuses on the change process of integrating these active learning strategies into a traditional lecture-based multidisciplinary course, called* Unified Engineering. *The description of the evolution of active learning in* Unified Engineering *is intended to underscore the motivation and incentives required for bringing about the change, and the support needed for sustaining and disseminating active learning approaches among the instructors.*

Index Terms — Active learning, change process, concept tests, muddiest point in the lecture.

INTRODUCTION

In the past decade, college and university faculty have shown great interest in teaching methods variously grouped under the term *active learning* [1–6]. In the Aeronautics and Astronautics Department at MIT, we define *active learning* as those teaching techniques that stress students' active involvement in their own learning. In our lecture-based courses, active learning includes individual strategies, such as cold calling, reading quizzes [7], and muddiest-point-in-the-lecture cards [8, 9]; and, cooperative strategies, such as concept tests [7] using an electronic response system [10], turn-to-your-partner discussions, and demonstrations.

Research on the benefits of active learning demonstrates that in addition to achieving learning objectives related to content, students develop abilities in communication, leadership, ethical decision making, and critical thinking [3]. Applications of this research in undergraduate engineering education are providing a rich and useful collection of best practices and guidelines. As an example, a search for "active learning" in the conference proceedings of the *American Society of Engineering Education* yielded 395 papers written in the last five years, and an average of ten papers per year appear in the *Frontiers In Education* annual conference sessions.

Despite the widespread application of active learning, some misunderstanding and mistrust remain. Bonwell and Sutherland [6] identified five major barriers to implementing active learning in the classroom as (1) the "coverage" problem; (2) increased class preparation time; (3) large classes; (4) limited, or lack of, resources and support; and (5) the risks of colleagues' disapproval, student dissatisfaction, and significance in promotion and tenure decisions. Additional challenges are introduced with the use of technology [11, 12].

In this paper, we describe the process of adopting active learning in *Unified Engineering*, a lecture-based, multidisciplinary core course for second-year students. We identify initial incentives to change, strategies to overcome barriers, and our selection of specific active learning strategies. Data from end-of-term course evaluations and instructor reflective memos provide evidence of the effectiveness and acceptance of active learning. We conclude with lessons we have learned about active learning in particular, and about the change process in general.

BACKGROUND

In 1996, all the faculty in our department participated in a strategic planning process, which culminated in a formal strategic plan for the department in 1998 [13]. The plan identified four major thrusts, two in research, and two in education. One of the educational thrusts, which we called "Learning-Based Education," was intended to improve the effectiveness of our teaching. The plan called for the department to:

1. Gain a better understanding of current scholarly work on learning, especially the learning of science and technology.
2. Base our educational programs on a more comprehensive understanding of technical learning.
3. Use our improved understanding of learning as a basis for improving our educational process and infrastructure.
4. Use our improved understanding as a basis for the rational introduction of new media into education.

Our strategy to achieve these goals was as follows: First, we believed that to succeed, the initiative must be part of

[1] Steven R. Hall, Professor, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, Room 33-315, 77 Massachusetts Ave., Cambridge, MA 02139-4307. E-mail: Steven_Hall@mit.edu.
[2] Ian Waitz, Professor, MIT, Department of Aeronautics and Astronautics, Room 1-266. E-mail: iaw@mit.edu.
[3] Doris R. Brodeur, Director of Learning Assessment, MIT, Department of Aeronautics and Astronautics, Room 37-391. E-mail: dbrodeur@mit.edu.
[4] Diane H. Soderholm, Instructional Designer, MIT, Department of Aeronautics and Astronautics, Room 37-375. E-mail: dhsoder@mit.edu.
[5] Reem Nasr, Research Assistant, Boston University, School of Education. Contact at: MIT, Department of Aeronautics and Astronautics, Room 33-409. E-mail: reemn@bu.edu.

a larger Engineering School-wide or Institute-wide initiative. Therefore, we resolved to help start an Engineering School-wide initiative on active learning techniques. Second, we actively sought established experts, both within the MIT community, and outside MIT, who could help us "jump-start" the process. Third, we concluded that the initiative must be a scholarly activity, with appropriate recognition and incentives for faculty who contribute to the effort. Finally, we decided that we would *not* concentrate our efforts on new media technologies, in part because of the perceived cost, and in part because of the rapidly changing status of these new technologies. Instead, we decided to monitor those currently breaking ground in new media, with the intent to build on their successes, and avoid their mistakes, in order to allow MIT to invest resources in this area prudently. For the most part, we have been able to successfully implement this plan to improve our undergraduate teaching. One of our biggest successes has been in *Unified Engineering*, the set of courses that comprise our sophomore core.

UNIFIED ENGINEERING

At MIT, students declare their majors at the end of the first year, and typically begin study in their major at the beginning of the sophomore year. In the Department of Aeronautics and Astronautics, the sophomore year is organized around four courses (two in the fall and two in the spring), collectively titled *Unified Engineering* [14]. *Unified Engineering* has a unique structure, in which five disciplines are taught throughout the year: Fluid Mechanics, Structures and Materials, Dynamics, Signals and Systems, and Thermodynamics and Propulsion. Each discipline has about 40 lectures spread between the fall and spring terms, except for Thermodynamics and Propulsion, which has 20. In addition, the students learn aspects of systems engineering and design through a series of interdisciplinary problems, called "systems problems." In the MIT credit system, each term of *Unified* carries 24 units of credit, which is equivalent to 8 credit hours. Enrollment in the department and *Unified Engineering* is cyclical, mostly due to the cyclical nature of the aerospace industry. In recent years, the enrollment has been about 60.

Unified has nine lectures each week. Most lecturers assign a textbook; many also provide lecture notes. Although students are encouraged to read the assigned material before lecture, most students do not, probably because of perceived time pressure. Each student attends two smaller "recitation" sections with 20–30 students in each section. Recitations are structured to give students opportunities to ask questions, and to work on example problems. There are frequent quizzes (eight or nine per term), and students turn in one problem set and one systems problem each week.

Students are encouraged to work together on problem sets and systems problems, so long as they give proper attribution to collaborators. Many students do work within a stable study group, and most work collaboratively at least some of the time. Because of the collaborative atmosphere, and the magnitude of the *Unified* experience, the class engenders an *esprit de corps* among students in the department that stays with them throughout their undergraduate years.

Because of the central role *Unified Engineering* plays in the undergraduate degree program, and the size of the course, *Unified* has a large staff. Each of the five disciplines is taught by a different professor. In addition, the systems component of *Unified* is coordinated by another faculty member. There are generally two graduate teaching assistants, and 8–12 undergraduate TAs who act primarily as graders, but also assist students during tutorial sessions.

Active Learning in *Unified Engineering*

Prior to 1998, a few faculty were sporadically using various active learning techniques, such as turn-to-your-partner exercises, in *Unified Engineering*. In the academic year 1998–1999, one of us began using active learning techniques more extensively in *Unified*. He used concept tests (or "ConcepTests") from the Peer Instruction method advocated by Mazur [7]. In this method, lectures are punctuated by brief, multiple-choice, conceptual questions to test student understanding of the material. When most students do well on a question, the lecture proceeds to new material. When the concept test reveals that students have conceptual problems or misunderstandings, students are encouraged to work in small groups to work out the answer to the question. Often, this peer instruction will help most students understand the material well enough to answer the concept test correctly. However, if many students still have problems, the instructor spends more time on the material. Initially, students used flash cards in *Unified* to show instructors their responses. During 1998–1999, the use of concept tests was sporadic, even in the single discipline using the technique. Nevertheless, student response was quite favorable.

In Spring 1999, many of the *Unified* faculty attended an MIT series on educational innovation, titled *On the Cutting Edge: Innovations in Science and Engineering Education*. The series was co-sponsored by a number of organizations within MIT, including the Teaching and Learning Laboratory, the School of Engineering, and the Department of Aeronautics and Astronautics.

Inspired by the modest success of active learning in *Unified* in 1998–1999, and new awareness by the faculty of the benefits of active learning gained from the *Cutting Edge* seminar series and faculty workshops, the faculty of *Unified* decided to try to incorporate active learning techniques more broadly, with all faculty using active learning techniques. During planning meetings in the summer of 1999, the staff considered a number of active learning techniques for possible inclusion into the course, and it was agreed that all would try some form of active learning techniques. During 1999–2000, each of the following techniques was used by at least one instructor in *Unified*:

- Concept tests
- Turn-to-your-partner discussions
- Cold calling
- In-class demonstrations

- Reading quizzes at the beginning of the lecture
- Muddiest-point-in the lecture cards

All faculty used the muddiest-point-in-the-lecture technique. Three instructors used concept tests or turn-to-your partner exercises.

At the time the faculty of *Unified* adopted active learning techniques, they confronted many of the same barriers identified by Bonwell and Sutherland [6]. Faculty were especially concerned about the amount of time the new techniques would take to implement; the ability to cover all or most of the syllabus; their lack of understanding of the techniques; and whether active learning techniques would be more effective than traditional techniques. We were able to surmount these barriers, in part, because of the unique structure of *Unified*. Because *Unified* is team-taught, and because of the high visibility of the course within the department, the decision to incorporate active learning into the course was, in effect, a public commitment. The accountability to the group engendered by this commitment led to both peer pressure and peer support to make the adoption of active learning successful.

The use of active learning in 1999–2000 was very successful, as judged by students in the end-of-term course evaluations, and by the faculty in their annual reflective memos. For the academic year 2000–2001, the faculty decided to adopt a more intensive and uniform approach to active learning. All faculty agreed to use concept tests and muddy cards in lectures.

Following a visit to Prof. Eric Mazur at Harvard to see his technique in action, we decided to replace the flash cards with the Personal Response System (PRS) brand infrared system [10]. In a typical classroom installation of the PRS system, each student has a hand-held infrared remote transmitter, much like a television remote control. During a multiple choice concept test, each student indicates his or her answer by pressing a single digit on the remote keypad. An infrared receiver connected to a personal computer collects the student responses, and displays the result in histogram form to the instructor. The instant feedback provided by the system makes it easier for the instructor to decide how to proceed after the concept test. The system also records the results of each concept test for later analysis. Another benefit of an electronic system is that student responses are confidential. That is, students do not know the responses of other students, but the instructor can determine each student's response. The system can also be set up so that the instructor only knows the histogram of response.

Figure 1 is a time line which summarizes the important events in the adoption of active learning techniques into *Unified Engineering*. In the sections below, we describe faculty and student responses to active learning in *Unified Engineering*. Most of the discussion focuses on concept tests and muddy cards, as these were the most commonly used active learning techniques.

Faculty Response to Active Learning

In this section, we describe the reaction of the *Unified* faculty to the adoption of active learning techniques. We quote heavily from *reflective memos* [15] written by the *Unified* faculty. Since Spring 2000, all instructors of undergraduate subjects in our department have been asked to write reflective memos at the end of each term, as a means of self-assessment, and to encourage faculty to think deeply about how to improve their teaching. Faculty are asked to describe the educational objectives of their classes, how they assess student learning against those objectives, the result of that assessment, and lessons learned.

Concept Tests

One of the difficulties faculty encountered was the problem of authoring new concept tests. In some fields, such as physics, rich sources of concept tests are available to the teaching community. (See, for example, [16].) Unfortunately, such sources are generally unavailable in engineering disciplines. Faculty noted these difficulties in their reflective memos:

> *I found the use of the PRS questions [i.e., concept tests] ... to be useful. My effectiveness on the PRS questions improved during the year. But it will take time to develop this pedagogy.*

> *I found it very difficult to create questions at the right level (i.e. probing concepts but only taking $<$ 5 minutes to answer).*

Despite the difficulty in creating good concept tests, faculty generally found them worthwhile:

> *From my perspective, the active component of the teaching was very effective. The in-class exercises mostly accomplished their goals, namely, to get students to confront their misconceptions, and to actively engage students in the learning process. My perception is that even when students did not understand the value of the exercises, it helped them focus on the issues at hand, and therefore facilitated learning.*

Faculty who used concept tests in 1999–2000 with flash cards generally felt that using a commercially available, automated response system would be beneficial:

> *I think that moving towards a more active teaching style has been beneficial, I intend to continue in this direction to the extent that I will work with [Prof. X] to use the infrared in-class feedback system for daily concept quizzes and I will continue to use the muddiest part of the lecture cards and turn-to-your-partner exercises. It is difficult to really know if you are improving and this system will provide a richer assessment database as well.*

In Fall 2000, we installed the Personal Response System (PRS) automated response system in our classroom, and all faculty in *Unified* agreed to use the system with concept tests. One faculty member, who had not used concept tests the year before, said

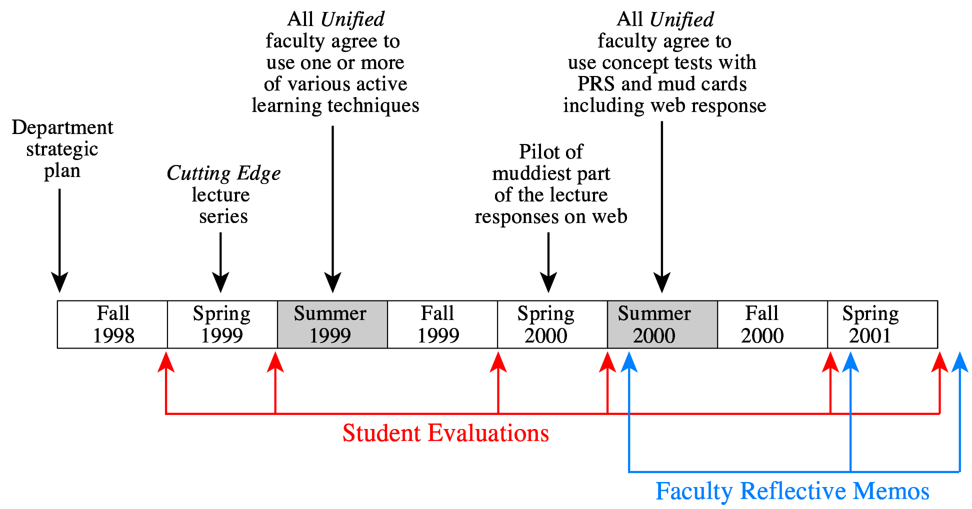

FIGURE 1.
TIMELINE OF EVENTS IN THE ADOPTION OF ACTIVE LEARNING TECHNIQUES IN UNIFIED ENGINEERING.

> *I used concept questions in every lecture I taught, with an average of 2.3 questions per lecture. I was initially skeptical of the PRS system but gradually warmed to it . . . . I will continue to use the system next year if it is available.*

Muddiest Point in the Lecture

Also in Fall 1999, the entire faculty of *Unified* began using the muddiest-point-in-the-lecture technique of Mosteller [8]. At the end of each lecture, students were asked to take two minutes to write the most confusing (or muddiest) point of the lecture on an index card, and hand it in to the instructor. Some instructors also asked students to identify the most important point of the lecture.

> *As with most of the other faculty who tried these I became an instant fan. I would scan the cards immediately after lecture and give feedback on the two or three most important/most frequent comments at the beginning of the subsequent lecture. This meshed well with my usual lecturing technique of beginning each lecture with a reprise of the key points from the previous lecture.*

Several faculty in *Unified* remarked that, after seeing the benefits of "muddy cards," they will never teach again without using them.

> *One difficulty we found using muddy cards in a large lecture class is finding the right balance in providing feedback to the class. An obvious strategy is to address common problems at the beginning of the next lecture. However, students who did not have difficulties often view this as a waste of their time. On the other hand, if some sort of direct response is not made, students may come to believe that filling out the muddy cards has no effect, and may stop filling out the cards. (Of course, even if no direct response is given to students, the feedback to the instructor is a valuable guide to shaping future lectures.)*

In part to address this problem, and in part to document common misconceptions in his discipline, one instructor began posting responses to the course web site in Spring 2000. In his reflective memo, he said,

> *In the Fall term, I found it difficult to adequately respond to muddy cards in class. If I answered a few questions at the beginning of each lecture, it took too much time, and was redundant for some students. If I didn't respond, students were frustrated that they weren't getting answers. This term, as an experiment, I answered every muddy question, and posted the answers on the web. The student feedback on this approach was extremely favorable.*

Given the favorable student reaction, most of the faculty in *Unified* planned to post responses to the muddy cards in 2000–2001, although this plan raised some concerns:

> *I had used muddy cards last year, and continued to do so. Unlike last year I posted the responses on the web* Unified *site . . . . I restricted the time taken to respond to muddy cards to be about 1–1.5 hrs per lecture — but this still added significantly to the time spent per lecture . . . . The utilization of the muddy responses was sporadic, although the positive perception it creates for the students might justify its continuing use.*

STUDENT RESPONSE TO ACTIVE LEARNING

During the process of implementation of the active learning techniques, students' attitudes toward, and their perceptions of, the curriculum modifications were assessed by examining their responses on the mid-term and end-of-term course evaluations. Much insight was gained into students' overall attitude toward active learning and their perceptions of its effect on their learning and on the learning environment.

When students were asked to comment on the teaching of the course or to compare the active learning techniques to the traditional lecture format, their responses reflected an overall positive attitude towards the active learning techniques. For example, one student described the techniques as "dramatically better than traditional blackboard format." Others specifically commented on the effect of the active learning techniques on improving their learning and understanding of the content, and in stimulating their thinking and classroom participation. Other students commented that:

> *Active learning is also a big plus since it gets students thinking in class instead of just taking in information.*

> *Taking time out to solicit feedback on a regular basis did wonders for my morale and enthusiasm.*

A few students did not find active learning techniques to be useful. One student described active learning as "irrelevant fluff," while another student believed that it "detracted from class-time" and "did not add to learning value enough." We found that student acceptance of active learning techniques improved when we carefully explained their purpose early in the course, and reinforced that explanation often throughout the term.

Concept Tests

In the Fall term of 1998, concepts tests using flash cards as the system of response were first used extensively by one instructor in *Unified*. Even though concept tests were not used in every lecture, students realized and noted their benefits:

> *[The instructor] made those [flash] card things so he could get a general feel of the class's understanding without embarrassing anyone.*

> *The [flash] cards with [Professor X] were ok. They awake the class, get them involved.*

In the following two years, concept tests were used more frequently, and by more of the faculty. By 2000–2001, all the faculty in *Unified* were using concept tests, with about two questions per lecture, and using the PRS infrared response system. Student feedback on the use of concept tests was generally more favorable when concept tests were used more frequently. When they commented on concept tests, students generally described them as a constructive way of engaging the students in lectures and as an efficient source of feedback in improving their learning:

> *Concept questions . . . are really great to help my understanding.*

> *Effective use of PRS is an awesome form of feedback.*

However, student comments on the course evaluations indicate that some students prefer concept tests that involve peer discussions, or other kinds of turn-to-your-partner exercises. They believe that solving problems in groups helps them to appraise their understanding and to improve their reasoning skills:

> *I think it is very important to observe how other people approach a problem to expand one's own ability to do so. It also makes the problems more enjoyable when we work together to figure out all the little nuances involved.*

> *I really enjoy working by teams because that way we can see the different ways of solving a problem. It also helps us learn how to explain our ideas on solving a problem and points out weaknesses in our reasoning.*

Moreover, students felt that the group work created a more enjoyable and collegial learning environment.

Muddiest Point in the Lecture

With regard to muddy cards, student views of the effectiveness of the muddy cards on their learning varied throughout the years of implementation. When muddy cards were first introduced in Fall 1999, few students noted a positive effect of muddy cards on their learning. However, in the following semester (Spring 2000), there was a marked increase in the favorable student comments that the muddy cards received. In that term, one of the instructors in *Unified* began posting summaries of the muddy points and brief explanations on the course web site. When students were asked whether the active learning techniques improved their learning the material of the course, about half who commented on the muddy cards found the web postings to be helpful to their learning:

> *Every [professor] should post answers to MUD cards. It's so useful.*

> *What Professor [X] did with muddy points, lecture notes and so on was great. If every professor did that, MIT would be the best school anywhere.*

From the students' point of view, the response to the muddy cards provided instant feedback. Perhaps as important was the message that posting summaries conveyed to the students. One student commented that "the [professor] really cared that we understood, he put things on the web." The theme of "caring" was evident in many of the student comments.

Interestingly, comments that reflect students' perceived value of muddy cards declined in the subsequent year (2000–2001), even though more of the faculty were posting summaries and responses. Although we cannot be certain, we believe that as other active learning techniques were implemented more effectively (especially concept tests), the muddy cards were less essential to students as a form of feedback.

Social Aspects of Active Learning

Comments during the following year (2000–2001) mainly involved attributions to the positive social dynamics engendered from the new learning environment. Students especially noted their closer relationships with, and the support of, their professors, teaching assistants, and other peers. As one student stated when asked to describe the best part of the course,

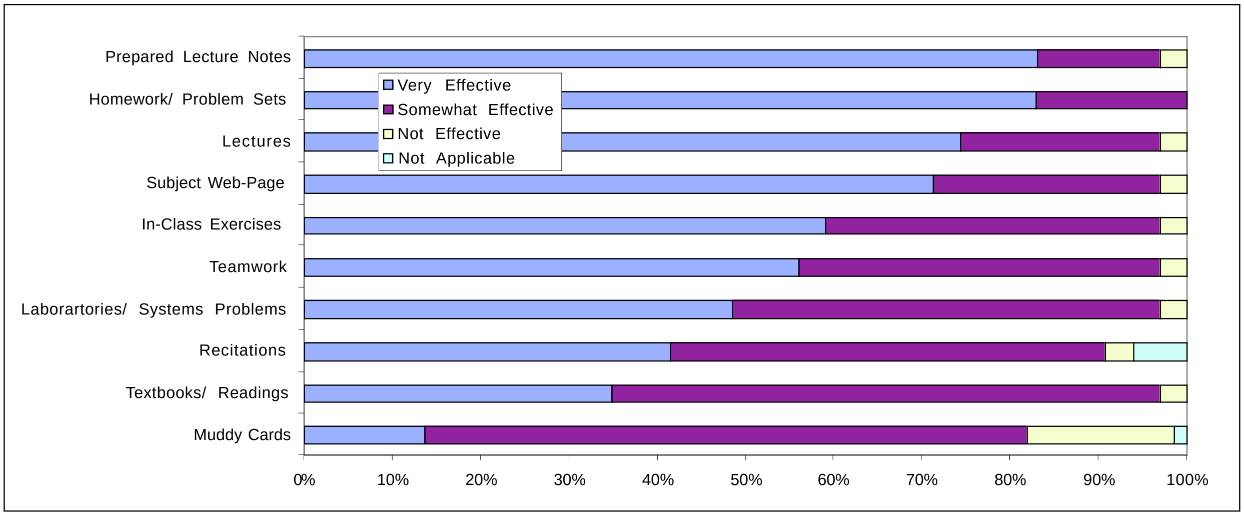

FIGURE 2.
STUDENT RATINGS OF VARIOUS TEACHING AND LEARNING TECHNIQUES IN UNIFIED ENGINEERING, SPRING 2001. (N=66)

Each one of the instructors and TAs seems truly dedicated to make Unified *a very positive learning experience for us, and they work very hard communicating with each other and with us to continually make it better. I see immediate results to feedback, and the faculty should be commended for the incredible job they do. I highly doubt there is another truly 'unified' engineering course as complex as ours that comes close anywhere, and that may be directly attributed to the staff.*

Even though similar comments were more numerous in 2000–2001, they were first noted when active learning was implemented by most of the faculty in 1999–2000. Students felt that professors "had genuine interest in their students," and that they "really cared" that their students understood the material. This result was striking for many of us who had taught in *Unified* for number of years, and had certainly cared about student performance before the introduction of active learning. Our interpretation is that the active learning techniques are the visible evidence that convinces students that we do care.

Comparison of Teaching Methods

In the Fall of 2000, questions on the end-of-term course evaluation forms were redesigned to generate more specific responses with respect to active learning. One of the questions was:

Q: How effective are these teaching and learning strategies in helping you deepen your understanding and achieve the learning objectives?

A list of the teaching strategies follows the question, and students are required to rate each as "not effective," "somewhat effective," "very effective," or "not applicable." Figure 2 summarizes the student response to the question for Spring 2001. (Responses for the Fall 2000 were similar.) Among traditional teaching methods, students rated prepared lecture notes and problems sets very highly, with more than 80% of students describing them as "very effective." Students also appreciated lectures and the course web page, with more than 70% rating them "very effective." Students rated in-class exercises (which includes both concept tests and turn-to-partner exercises) highly, with 58% rating them as "very effective," and more than 95% rating them as "somewhat effective" or "very effective." Only 13% of students rated muddy cards as "very effective," although most students (82%) rated them as "very effective" or "somewhat effective." This result was a surprise to us, given the very favorable response muddy cards received in 1999–2000. As mentioned above, we believe this result reflects the improvement in in-class feedback through concept tests and turn-to-partner exercises.

Comparison of student attitudes before and after the adoption of active learning in *Unified* are difficult, due to confounding variables, such as changes in personnel and changes in the student evaluation instrument. Prior to 1999, *Unified* was well-regarded by the students. For example, in the Fall term of 1998, *Unified* received an overall course rating of 5.2 out of 7. In the Fall term of 1999 (after the adoption of active learning), *Unified* received an overall course rating of 5.9 out of 7. In the Fall term of 2000, *Unified* received a rating of 4.7 out of 5 in the category "overall the subject is worthwhile." Student open-ended responses over that period generally indicate a higher appreciation for the course after adoption of active learning.

CONCLUSION AND LESSONS LEARNED

There are several lessons which our department has extracted from this experience. Perhaps most important is a recognition that changing *how* we teach is more difficult than changing *what* we teach. Barriers to changing how we teach included a general lack of knowledge about learning among our faculty and students, fear of the uncertainty that comes with change (both faculty and students), reluctance to devote the additional time that change requires, and lack of specific data in many instances to assert that change would be helpful.

Specific actions that were helpful in lowering barriers to change included participation by all department faculty members in a careful strategic planning process that led to a mandate for change, as well as an environment within our department and the Institute where excellence in teaching is increasingly valued and rewarded. Thus, throughout the process we had strong support from our administration. This included, in some instances, release from other duties to enable faculty members to focus on these activities. The strategic plan told us we should do something, but it didn't tell us exactly what to do or how to do it. Bringing in outside experts as speakers and full-time staff members was helpful for both defining the detailed implementation plans and formulating data-based arguments to support specific actions. We also actively courted opinion leaders within the department to serve as early adopters for many of the changes.

Within *Unified*, the team teaching environment was a particularly effective incubator for change. It provided both peer pressure and peer support. *Unified* has been the flagship course in our department for over 25 years. Thus, there was a high degree of interest in our activities from both faculty and students, and it served as a prominent example for the rest of the department. As we implemented the changes, most of our attention and support was on the faculty members. In retrospect, we should have spent more time educating students about why we were doing what we were doing, and providing support for them as we changed the learning environment from something they were familiar with to something new. We eventually did this, but a little later than desired. In terms of the specific techniques we applied, the overarching message is that active learning was helpful. Muddy cards are easy to implement and effective, and concept tests, while often difficult to formulate, are also effective.

In summary, understanding about learning (*e.g.*, dominant learning styles for engineers and the value of active learning), and adopting best practices (*e.g.*, learning objectives that focus on measurable outcomes, faculty reflective memos, and muddy cards) can be very beneficial. Overcoming barriers to change requires careful planning, implementation, hard work, and even occasional arm-twisting to ensure success.

ACKNOWLEDGMENTS

In addition to two of the authors (Hall and Waitz), Profs. Earll Murman, Wesley Harris, Mark Spearing, Walter Hollister, Winston Markey, Charles Coleman, and James Kuchar were instructors in *Unified Engineering* between 1999 and 2001. The authors gratefully acknowledge their contributions to this effort.

REFERENCES

[1] Bonwell, C. C., and Eison, J. A., *Active Learning: Creating Excitement in the Classroom*, ASHE-ERIC Higher Education Report No. 1, George Washington University School of Education and Human Development, Washington, DC, 1991.

[2] Faust, J. L., and Paulson, D. R., "Active Learning in the College Classroom," *Journal of Excellence in College Teaching*, Vol. 9, No. 2, 1998, pp. 3–24.

[3] Hake, R. R., "Interactive Engagement vs. Traditional Methods: A Six-Thousand-Student Survey of Mechanics Test Data for Introductory Physics Courses," *American Journal of Physics*, Vol. 66, No. 1, 1998, pp. 64–74.

[4] Meltzer, D. E., and Manivannan, K., "Promoting interactivity in physics lecture classes," *The Physics Teacher*, Vol. 34, 1996, pp. 72–76.

[5] Meyers, C., and Jones, T. B., *Promoting Active Learning: Strategies for the College Classroom*, Jossey-Bass, San Francisco, 1993.

[6] Bonwell, C. C., and Sutherland, T. E., "The Active Learning Continuum: Choosing Activities to Engage Students in the Classroom," in Sutherland, T. E. and Bonwell, C. C., (Eds.), *Using Active Learning in College Classes: A Range of Options for Faculty, New Directions for Teaching and Learning*, No. 67, Jossey-Bass, San Francisco, CA, 1996.

[7] Mazur, E., *Peer Instruction: A User's Manual*, Prentice Hall, 1997.

[8] Mosteller, F. "The 'Muddiest Point in the Lecture' as a Feedback Device," *On Teaching and Learning: The Journal of the Harvard-Danforth Center*, Vol. 3, 1989, pp. 10–21.

[9] Angelo , T. A., Cross, K. P., *Classroom Assessment Techniques: A Handbook for College Teachers* , 2nd Edition, Jossey-Bass, San Francisco, 1993.

[10] *EduCue Home Page*, http://www.EduCue.com/Home.htm, 2002.

[11] Novak, G. M., Patterson, E. T., Gavrin, A. D., and Christian, W., *Just-in-Time Teaching*, Prentice-Hall, Upper Saddle River, NJ, 1999.

[12] Poulis, J., Massen, C., Robens, E., and Gilbert, M. (1998), "Physics Lecturing with Audience-Paced Feedback," *American Journal of Physics*, 66, pp. 439–441.

[13] *Strategic Plan*, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 1998.

[14] Hollister, W. M., Crawley , E. F., and Amir A. R., "Unified Engineering: A Twenty Year Experiment in Sophomore Aerospace Education at MIT," *Journal of Engineering Education*, Vol. 4, No. 1, Jan. 1995, pp. 13–19.

[15] Edgerton, R., Hutchings, P., and Quinlan, K., *The Teaching Portfolio — Capturing the Scholarship of Teaching*, American Association of Higher Education, Washington, DC, 1991.

[16] *Project Galileo*, http://galileo.harvard.edu/, 2002.