Testimony offered by Elaine Seymour, Ph.D., University of Colorado at Boulder, to the Research Subcommittee of the Committee on Science of the U.S. House of Representatives Hearing on ***Undergraduate Science, Math and Engineering Education: What's Working?***
Wednesday, March 15, 2006.

The Research Subcommittee has asked me to address the following questions:

- What has your research shown about why potential science majors drop out of undergraduate science programs?
- What changes in undergraduate science education could prevent capable students from leaving science disciplines and perhaps also attract students initially not interested in science? What are the principle obstacles to implementing these changes?
- What role have federal agencies, particularly the National Science Foundation, played in improving undergraduate science education? What more should federal agencies be doing in this area?

On the basis of my work as a science education researcher and as an evaluator of both campus-based and large national initiatives focused on improving quality and access in undergraduate science education, I offer some answers to these questions under the following headings:

1. Factors that shape the quality of undergraduate science, technology, engineering, and mathematics (STEM) education
2. Their consequences for current and future STEM undergraduates
3. Strategies (both underway and needed) that address current difficulties
4. Some caveats: why are some changes difficult to secure

## 1. Factors that shape the quality of undergraduate science, technology, engineering, and mathematics (STEM) education

Two inter-related factors—one cultural, the other structural—underlie the problems with undergraduate science education that have been identified over the last two decades. These factors also explain some of the difficulties encountered by those who seek to improve STEM education, both at the undergraduate and K-12 levels. The first may be described as a history of **decline in the perceived value of teaching.** Among STEM faculty, teaching has come to be seen as a far less important part of their professional role than research, and STEM faculty overall do not encourage K-12 mathematics and science teaching as a career for their STEM graduates.

In our study of why undergraduates leave the sciences (Seymour & Hewitt, 1997), we noted that, although almost 20% of our student sample had seriously considered science or mathematics teaching, this dropped to under 7% in senior year among those who persisted in their STEM majors. A major factor in this decline was students' awareness that their professors—whose approval and support they sought in developing a career path—defined teaching ambitions as "deviant." Faculty were commonly believed to withdraw from students who openly expressed an interest in K-12 teaching and those who still intended to teach become covert about their intentions:

> I think that's ultimately the problem with math and science in this country—we don't value teachers enough. Professors are valued but the high school teachers are not. If you wanna teach science in high school, that's taboo: you're treated as an outcast by the faculty here. (male white switcher)
>
> I've never discussed it with any of my chemistry professors. For the most part, I've got a feeling of disdain for teaching from them. This is something that they have to do, but they don't really support anyone who wants to do it. Fortunately, I had an incredible chemistry teacher in high school, and I go back and chat with him still. He tells me, You're going to be a good teacher." I get more encouragement from him than from anyone on campus. (Male white science persister)

Students who wanted to teach also described discouragement from family members and peers who perceived teaching as a career with low status, pay, and prospects. Students of color were the only STEM seniors who reported encouragement from faculty and advisors to become K-12 teachers.

With respect to faculty's own work, the balance of status and rewards has, over time, tipped heavily towards research and away from teaching. Although lecturing has historically been the dominant mode of instruction, it was traditionally supported by various forms of interactive small group teaching such as tutorials and seminars, and by advising and mentoring of students on an individual basis. The pressure to spend more time on research has led to the dwindling of these interactive teaching functions among faculty, and their devolution to (largely untrained) teaching assistants (TAs). Thus "straight lecturing" (often in classes of several hundred students) has increasingly become faculty's main or sole mode of teaching.

This trend has its roots in the 1950's and '60's when university research (which was previously mostly privately funded) began to receive progressively large amounts of funding from the federal government to carry out large-scale basic research and as projects with both military and industrial/commercial relevance (Kevles, 1979; Fusfield, 1986). Professional success in academe is now clearly defined in terms of research grant writing and publication. This imbalance is reflected both in the **salary structure,** in which many faculty raise a proportion of their salaries by grant writing, and in **the departmental and institutional rewards systems for tenure and promotion** in which research achievements both outweigh and are more stringently defined than teaching or service work. Scholarship in teaching is barely developed and under-acknowledged as a criterion for faculty rewards (Boyer, 1990). The main mechanism by which teaching effectiveness is judged, namely student course evaluation surveys administered by institutions, are widely acknowledged to be poor measures of teaching performance and even poorer measures of student learning gains (Kulik, 2001).

The consequences of this situation have not gone un-noticed. Concerns about the quality of STEM undergraduate education have been raised in a number of reports, notably, those of the National Science Foundation (*Shaping the Future*, 1996), the National Research Council (*Transforming Undergraduate Education*, 1999; *Improving Undergraduate Instruction in Science, Technology, Engineering, and Mathematics, 2003*), and, most recently, the National Academy of Sciences (*Rising above the Gathering Storm*, 2005). There has also been a rising demand for course assessment tools that more accurately reflect student learning (Hunt & Peligrino, 2002) by accreditation boards (and others) who no longer view faculty grades as acceptable evidence of student learning. State legislatures have also expressed concerns about the quality of undergraduate education and departments are increasingly called upon to define objectives for student learning and demonstrate their attainment (Wergin, 2005; Peterson and Einarson, 2001).

Although many STEM faculty are currently seeking to improve the effectiveness of their teaching and to develop more accurate ways to assess their students' learning, they do so in the face of deterrents in the faculty rewards structure. In our interview studies, pre-tenured faculty commonly report that they are strongly counseled by their mentors to defer an interest in teaching until after they gain tenure—often seven or so years into their careers. In our evaluation work for two of the five major chemistry initiatives sponsored by the National Science Foundation[1] that have developed and tested modular materials and methods for the teaching of undergraduate chemistry, three active young faculty contributors to that initiative were denied tenure on the grounds of their "over-focus" on educational scholarship (Seymour, 2001). Panelists and participants at the 1998 National Institute of Science Education Forum (NISE) on the future of STEM education concluded, with regret, that younger faculty should be advised to defer their interest in improving their teaching and assessment methods and avoid the introduction of education scholarship into their tenure portfolios (NISE, 1998).

## 2. Consequences for current and future STEM undergraduates

The lower value placed on teaching compared with research both in STEM faculty attitudes and in academic salary and rewards structures has consequences for the quality of both undergraduate and K-12 education in science and mathematics.

### A. STEM undergraduates' problems with their learning experiences

In *Talking about Leaving: Why Undergraduates Leave the Sciences* (1997) we discussed our findings from a study of field-switching and persistence among well-qualified students (i.e., those with SAT mathematics scores of 650 or above) who entered science, mathematics and engineering majors in seven institutions of different types. Across all seven campuses, we found that reports of poor learning experiences were by far the most common complaint **both** of those who switched out of science, mathematics, and engineering majors (90%) **and** graduating seniors in those majors (74%). Undergraduates' problems with what they referred to as "poor teaching" ranked first among 23 types of problems with their majors identified by graduating seniors in six of

[1] The ChemLinks Coalition ("Modular Chemistry: Learning chemistry by doing what chemist do") and the Modular Chemistry Consortium, now combined as "ChemConnections."

the seven institutions. Unsatisfactory learning experiences in their science and mathematics courses were the primary cause of switchers losing their incoming interest in the sciences, and moving into disciplines where they had better educational experiences. The students' concerns about how their courses were taught focused on the following issues:

- Courses (and the curriculum overall) were over-stuffed with material and delivered at too fast a pace for comprehension, reflection, application, or retention
- Insufficient attention was paid to class preparation, appropriate level and depth in the selection of class content and materials, or logical sequencing in its presentation
- Lack of "fit" between class and lab objectives and content and lack of explanation to students of the conceptual connections between them; (students commonly reported that they did not know why they were conducting particular lab experiments); and lack of coherence between course content and tests, the text, and/or homework
- Little application, illustration, or discussion of conceptual material
- Curve grading systems that disengaged grades from learning and from students' perceptions of mastery; that created artificial and demoralizing forms of competition; and made collaborative peer learning difficult
- Faculty showed or expressed dislike or disinterest in teaching
- Faculty appeared to distance themselves from under-classmen, and seemed insufficiently available for help and advice
- Faculty modes of teaching suggested that they took little responsibility for student learning, such as checking to see if students were understanding class material
- Faculty showed little knowledge of the use of learning objectives or pedagogy other than lecturing
- Able students became bored by their introductory science courses despite their strong incoming interest in science
- Many students developed instrumental attitudes to learning focused on grades rather than mastery, cheated to beat the curve, and did not retain content knowledge that they memorized mainly for tests.

The aspects of introductory classes that discouraged young women were different from those that deterred young men from continuing in STEM majors (Seymour, 1995; Seymour & Hewitt, 1997). Broadly the features of faculty teaching that reflected the weed-out system (such as fast pace, work and content overload, harsh competition created by curve grading) were far more effective in prompting male students to switch. Young women suffered rapid loss of their incoming confidence because they were unable to establish with their professors the kind of interactive learning and support they had enjoyed with high school teachers. Faculty's failure to encourage was taken as discouragement. This was compounded in departments where hostile treatment from male peers was a daily experience. Able women quickly came to doubt whether they belonged in the major, and doubts shared with their families provoked more encouragement to switch out of the sciences than was experienced by similarly placed male peers. The result in our own university was that women were switching out of STEM majors with higher average PGPA scores than the men who persisted in them.

We concluded that problems with the quality of undergraduate education especially in the freshman and sophomore years were a major determinant of the consistently high field-switching rates (40% to 60%) reported for STEM majors in the *American Freshman* studies of the Higher Education Research Institute, UCLA (HERI. 1992). The students' descriptions of their experiences and their responses to them were also consistent with the view (directly articulated by some students) that many faculty disliked teaching, did not value it as a professional activity, and lacked incentives to learn how to teach effectively:

> About the end of the semester he said, "I guess by now you've all realized that the university is not for teaching students." He put it plain, right out in the open…In effect, he was telling us, "If you want to succeed here, you're going to have to do it by yourself." (male, white, science senior)

The students also reported experiences with science faculty who seemed to enjoy their teaching, took pains to be well organized and clear, and who took an active interest in their students. Seniors were, however, aware of the research pressures on their professors that limited the time and energy they could give to teaching. They were less aware of the tenure and rewards system that makes it difficult for faculty interested in education to improve their pedagogy or that makes it a highly risky form of activity for pre-tenured faculty.

**Some caveats**: Students can only describe their classroom problems in light of what they know about teaching and learning from current and prior experience. For less well-prepared students, their undergraduate STEM course experiences often mirror in an extreme form the limitations of their high school science learning experiences. These are characterized by passive reception of information (rather than active engagement with ideas), minimalist attitudes to reading and writing, formulaic approaches to learning focused on memorization rather than conceptual grasp, and carrying out tasks rather than thinking. Students also lack a conceptual framework based in cognitive science research to explain why the pedagogy they have experienced does not enable their learning. Most students in the study simply did not know what other modes of teaching and learning might be available and regarded the lecture format as an inevitable part of undergraduate life. Lack of knowledge of what alternative pedagogical methods would entail, helps to explain why, when faculty begin to address the problems students identify by teaching in ways that require more active student engagement and responsibility, students often resist these unfamiliar, more demanding pedagogies—at least initially. Better the devil you know…

How some STEM faculty have responded to their students' learning problems that they also have recognized is discussed in the next section.

**B.** The lower level of importance that faculty assign to their teaching role (whether by choice or career necessity) is also reflected in **inadequate educational preparation of graduate students for their roles, either as teaching assistants (TAs), or as young faculty** (despite faculty's increased dependence on TAs to provide interactive learning support to students). As I have recently outlined (Seymour, 2005) the need to prepare

TAs was first mooted in the 1930's and it continued to be proposed throughout the following decades. However, in a historical review, Nyquist, Abbott and Wulff (1989) comment on the slow progress of universities to provide formal professional development for teaching assistants. After the first national conference on TA issues in 1989, more universities began to offer TA preparation in an effort to improve undergraduate education. However, the available research (summarized in Seymour, 2005, Chapter 10) indicates that most institutions and disciplines either do not offer formal educational preparation for their TAs or offer programs that are informal or limited in scope—most commonly, short orientation sessions that are not discipline or course specific. Furthermore, most existing programs do not ground TAs in learning research and the teaching practices that derive from this body of knowledge. Most TA training (sic) programs give advice on management of their lab and recitation sections that are relevant only to the lecture mode. Although the STEM disciplines are major employers of TAs in their large introductory classes, Shannon, Twale, and Moore (1998) found that TAs in science, mathematics, and engineering classes were the least likely to receive appropriate educational preparation for their teaching support work. This ongoing situation significantly contributes to poor quality undergraduate learning experiences—notwithstanding the importance of TAs' to their learning and academic survival as attested by STEM undergraduates (Seymour & Hewitt, 1997).

**A large body of cognitive research and practice exists** upon which STEM faculty can draw in rethinking their own teaching and in developing appropriate educational preparation for their TAs. Broadly, research on learning proposes that students progressively build a personal knowledge framework based on what they already understand, and, that conceptual mastery and resolution of misconceptions is best accomplished in active engagement with ideas and problems, including interactive exchanges with teachers, TAs, and peers. Strategies that reflect the findings of cognitive science include a shift in approach from teaching to enabling learning, a focus on problem-based and contextual learning, on inquiry and hands-on discovery, and reduction in the breadth of "coverage" in favor of strategies that encourage deeper understanding. Students are also encouraged to connect and apply their knowledge and to take more responsibility for their own learning. Teachers are encouraged to articulate their learning objectives, match their selection of materials, content emphases, and learning assessments to these, make their learning objectives and expectations clear to students, and "signpost" for students the intellectual path they are taking through the content (Seymour, 2001). Teaching methods derived from this body of theoretical and applied knowledge is increasingly referred to as "scientific teaching." The available literature is too large to summarize here, but, in addition to theoretical and research publications, it includes descriptions and evaluation results from STEM faculty's endeavors to implement these principles in their approaches to the teaching and development of class and lab materials and methods—a body of work that constitutes a growing scholarship of education among an active minority of STEM faculty.

Both the research and its application and outcomes have, in recent years, been offered in forms that are very accessible to faculty who are interested in understanding more about how students learn and how best to enable learning in their own teaching work (reviewed

by DeHaan, 2005; Handelsmith et.al, 2004). Strategies for teaching student to be active, interactive, and independent learners, and for designing problem-based, inquiry-focused class and lab work are offered on a number of websites, for example: http://thinkertools.soe.berkeley.edu, www.udel.edu/pbl/, www.bioquest.org, www.provost.harvard.edu/it_fund/moreinfo_grants.php?id=79
Information about *workshops* that give faculty hands-on experience in using active learning methods (including working with chemistry modules) is available at www.cchem.berkeley.edu/~midp Some websites focus on *particular disciplines*:
In chemistry: http://chemconnections.llnl.gov, PLTL: www.sci.ccny.cuny.edu/-chemwkssp/nde.html, CPR: www.molsci.ucla.edu/default.htm, OGIL: www.pogil.org/
In physics: TEAL: http://evangelion.mit.edu.edu/802TEAL3D, SCALE-UP: www.ncsu.edu/per/scaleup.html
In biology: BioSciEdNet(BEN): www.biosciencenet.org, Bioquest: www.bioquest.org/BQLibrary/bqvolvi.html, undergraduate bioinformatics: www.cellbioed.org/article.cfm?ArticleID+157 Others sites (such as those offered by the University of Wisconsin at http://ww.wcer.wisc) offer assistance to faculty in designing *learning assessments* (tests, projects, etc.) that reflect course learning objectives (using the "Field-Tested Learning Assessment Guide); and in obtaining feedback on the degree to which *students assess their learning gains* in particular aspects of their courses (the on-line "Student Assessment of their Learning Gains" instrument). I have been closely involved in the development of both sites and attest to their widespread use by STEM faculty. The University of Wisconsin Center for Education Research also houses websites offering practical advice to faculty in collaborative learning methods and in the use of technology in their classrooms.

Notwithstanding its growing availability, this knowledge is still unknown to and unused by many, perhaps most, STEM faculty, and the knowledge and expertise of education faculty at their own institutions is often ignored or discounted. Failure to convey this knowledge to TAs perpetuates in the next generation of faculty the limited knowledge of research-grounded teaching practices and limited priorities that characterize current faculty teaching. Both our TA study, and that done by French and Russell (2002), note how quickly graduate students can develop misconceptions about how learning takes place, and assume unfortunate attitudes towards teaching that they observe in their professors. Once established, these prove hard to dislodge. Hammrich (1996) found that TAs commonly believe student understanding to be a matter of "automatic transmission or absorption" rather than an "active process of interpreting information and constructing understanding" (p.8). One (happily minority) source of TA resistance to the methods which they were being taught to use in the innovative science courses included in our study was that the requirement that all TAs use the same active, interactive, inquiry-based methods in their lab and recitation sections. This affronted some TAs' presumption that, like faculty, TAs had the right to teach however they saw fit. Creating change in the existing STEM faculty, though not (as I shall later argue) impossible, is a more difficult endeavor than choosing to give graduate students an adequate education for their present and future teaching roles that is grounded in a researched-based understanding of how students learn.

**C. STEM Undergraduate under-preparation and limitations of the K-12 teaching force.**

Lack of faculty support for science and mathematics teaching careers among their STEM majors, coupled with a historic decline in the number of high ability women entering mathematics teaching (noted by Schlechty and Vance as early as 1983), and perceptions of lower status and pay for K-12 teachers in the general American population, have combined to create a serious shortfall of discipline-qualified mathematics and science teachers in middle and high schools. The situation has been well-documented over the last decade (e.g., Gafney and Weiner, 1995; Schugart & Hounsell, 1995; Clewell & Villegas, 2001), and was most recently cited in the National Academy of Sciences report, *Rising above the Gathering Storm* (2005).

Problems of shortage are compounded by concerns about quality. The 1990-91 Schools and Staffing Surveys (SASS) warned that 72% of public secondary school mathematics teachers and 38% of science teachers had not earned a bachelor's degree in their disciplines and that those with a disciplinary qualifications were an aging group that was not being replaced by entrants to the profession. In 1997, the US Department of Education reported that 39% of school districts had vacancies for mathematics and science teachers which 19% had been unable to fill. In that year also, President Clinton addressed the issue in his State of the Union address, urging that, "We should challenge more of our finest young people to consider a career in teaching." Whether in response to this appeal or to a downturn in the job market, the numbers of non-STEM baccalaureate entrants to the teaching profession rose appreciably. However, this was not the case for science and mathematics teachers where the shortfall continued to worsen. In 2000, the results of a National Science Teachers' Association nationwide survey showed that 61% of high schools and 48% of middle schools were experiencing difficulty in locating qualified science teachers to fill vacancies and that many schools were obliged to fill vacancies with less qualified or temporary teachers. In 2004, Bruillard reported that in-need districts were importing international K-12 teachers to fill their mathematics and science vacancies. The situation has been most acute in schools with more than 20% minority enrollment (Clewell & Villegas, 2001). States such as Texas, Florida and New Jersey with high mathematics and science teacher vacancies have turned to alternative or emergency certification of people with some STEM background, such as retired military personnel. Most recently, the National Academy of Sciences (2005) report warned that only 41% of US middle school students had a mathematics teacher with a major in the subject, while, internationally, the average is 71% and in many countries is greater than 90%.

The consequences of the shortage of qualified mathematics and science teachers in middle and high schools was evident in our *Talking about Leaving* study findings. The discovery of a gap between the levels of knowledge with which students had graduated from their high schools and those demanded of them in introductory college mathematics and science courses was a common experience. However, it was evident that, in 39% of all student statements about problems with their educational experiences, the gap reflected serious under-preparation. There was no difference between the switchers (40%) and the persisters (38%) in this regard. However failure to find remedial help from a tutor, study group, or other means in order to make up the gap was mentioned as a factor in switching.

Many switchers and persisters who had taken Advanced Placement mathematics and science courses were shocked to find that these courses had been offered at too low a level to adequately prepare them for their first college courses. Their experience is echoed in findings of significant variations in the quality of AP course reported by Juillerat et al. (1997). There were also regional and race/ethnicity patterns in our findings on under-preparation problems. Students at the east coast state university in our sample experienced the greatest variability in the reliability of their high school science and mathematics grades as an indicator of their college-level work. They expressed frustration that neither they nor their parents could have known the extent of their under-preparation from their grades or their teachers' evaluations of their work. Students of color from high schools predominantly attended by students of the same race/ethnicity were at particular risk of a phenomenon that we labeled, "over-confident and under-prepared." Teachers, parents, and community members had sent students to college with a strong sense that they could succeed in STEM majors, only to find that their science and mathematics preparation seriously undermined their chances. This group gave some of the most heart-rending accounts that we heard in this study of their failed efforts to close the preparation gap. Rather than identifying inadequacies in educational provision as the cause of their problems, most of these students blamed themselves. These students were at high risk, not only of switching, but of dropping out our college altogether. Faculty attitudes towards students whose misfortune it was to receive inadequate preparation also played a role in the loss of able students. Questioning the adequacy of their high school preparation was highly evident at institutions where we found the weed-out tradition to be strongest: loss of confidence and discouragement engendered by low grades were highly ranked as a cause of switching in the two western state universities where weed-out assessment practices were strong, particularly in the colleges of engineering.

Teaching assistants in our 2005 study also struggled with high variability in the high school preparation of the undergraduates with whom they worked in recitation and lab sections. The 42 chemistry TAs at the University of California, Berkeley who were helping to prepare students to enter chemistry majors, expected undergraduates to enter the course with sufficient knowledge and skills in chemistry and mathematics to undertake the class work. They assumed that students would be able to solve problems, operate in the lab, write lab reports, and tackle unfamiliar problems by using what they already knew. In all of these expectations, they were disappointed. More than two-thirds of the Berkeley TA sample reported that students arrived under-prepared in the fundamental knowledge and skills needed to perform at least adequately. Their direct experience with students in their lab and recitation sections led them to conclude that many did not posses an understanding of the methods and principles of science and some could not do elementary algebra. TAs also noted that the writing and study skills of some students were poor. Overall, less than one-third of the TAs working in this large introductory chemistry class felt that most of their students entered the course with the requisite knowledge and skills to undertake it:

> A lot of these students have problems, not just with the math, but with basic algebra and with manipulating equations to get things in the right form and so on. And the class assumes that they know how to do that kind of thing.

Concern that their first- and second-year students entered their classes under-prepared for their course work was also documented in a survey of 314 TAs in forty-five courses at the University of Nebraska, Lincoln (Luo, Bellows, & Grady, 2000) in which (as at Berkeley) two-thirds of the TAs assessed their students as under-prepared. By contrast, the Berkeley TAs noted that some students were over-prepared for this introductory course. Indeed, the TAs' largest single teaching difficulty was the wide variation that they encountered in the levels of preparation in mathematics, science, writing, and study skills that their students had received from their pre-college education. Their testimony underscores the problems both of widespread under-preparation in middle and high school mathematics and science, and of significant regional and local disparities in the quality of mathematics and science education offered.

The 110 TAs included in our study were generally not disposed to blame the students for inadequate preparation and we document their efforts to help their students make up for lost ground. However, we also note the irony of those STEM faculty who treat under-preparation as an indication of students' lesser worth given the contribution of STEM faculty as a whole to the continuing shortage of adequately qualified K-12 science and mathematics teachers. In light of the problems this shortage creates for access, quality, and persistence in undergraduate STEM education, I propose that rethinking the roles and professional development of teaching assistants offers an opportunity to break part of the cycle that has simultaneously perpetuated the decline in the perceived value of teaching, diluted the quality of undergraduate STEM education, and constrained the building of a discipline-educated teaching force in science and mathematics that is adequate to national needs.

### 3. Strategies (both underway and needed) that address current difficulties

Given my foregoing diagnosis of factors contributing to problems in the quality of undergraduate STEM education, I focus on three main areas of activity that seem to offer the best promise of improvement. All three involve active efforts in the professional development of teachers─current and future K-12 science and mathematics teachers, teaching assistants in STEM undergraduate courses, and STEM faculty─based on methods grounded in research on how students learn.

**First some caveats**: Faculty will always be at varying stages of readiness to change their thinking and attitudes about teaching and learning or consider new practices. Some are already active; others interested, curious, or skeptical; and some will remain firmly committed to current teaching methods regardless of the evidence as to the benefits of alternative approaches. Providing clear and convincing evidence that innovative forms of teaching are as effective or better than more traditional approaches is always a necessary but not a sufficient condition for change. The idea that good ideas, supported by convincing evidence of their effectiveness, will spread 'naturally' as their success becomes know, is unfounded. As Kuhn (1970) noted, shifts in scientific theory do not occur as an automatic response to accumulations of data. When the shift that is called for is one of values, attitudes, and social behavior, the response is, as Tobias (1992) observed, often unaffected by available evidence. Indeed, there is research evidence that the personal endorsement of classroom innovations by colleagues who are esteemed for their *research* standing is more effective than evidence presented in scientific articles or direct demonstrations of the superior outcomes of particular methods (Foertsch et al., 1997). Thus, change of whole departments or institutions in the same time frame is apt to be difficult, and may prove impossible.

Although I am aware of some STEM departments where every member is actively implementing new forms of teaching and learning, these are a small minority. In most departments, innovation-minded faculty will be a minority. Whether changes are mooted by more radical colleagues, by institutional or state leaders, or by outside agencies, departments in which the majority are committed to the status quo can effectively resist change. (The exception seems to be accreditation boards who can and do exercise effective leverage.) Departments have the power to resist change, partly because of the established tradition of faculty post-tenure autonomy in matters of academic and professional judgment, and partly because reference to disciplinary standards and practices can be argued by department members to supersede other authorities.

These difficulties suggest two lines of action:

a). Following the argument already laid out, I urge the **design and implementation of department-based, discipline and course specific, programs for the professional development and support of teaching assistants** (STEM and otherwise). This preparation should expose them to cognitive science research on student learning, the range of teaching approaches and specific methods that this knowledge supports, and offer guided practice in working interactively with students to enable their learning. In the view of the TAs in our 2005 study, education preparation and support programs were best when attached to the faculty and the course that each TA served rather than broader preparation in departmental or campus-wide programs not related to their working experience. As argued earlier, this strategy holds the promise of preparing the next generation of faculty more appropriately and adequately for their teaching role than their predecessors and will make the diffusion of effective educational methods progressively easier with each generation of STEM graduates.

A set of suggestions for what such a course might contain for TAs who are working with faculty who are implementing innovative courses was offered by TAs in my 2005 study. Grounded in their experience, they sought a course that would:

- introduce them to the scholarship of learning and the educational practices that support student learning
- give clear guidance as to the principles and methods of the course they are to work in, its learning objectives, and the methods and materials to be used in working with students

- model for them pedagogical skills and techniques for working interactively with students
- guide them in dealing with common problems─handling questions to which they do not know the answers, disruptive or non-participative group members, and disciplinary problems
- prepare them working alongside faculty for new activities, such as inquiry-based labs and teaching students to work with authentic data
- offer practice and feedback on their work
- enable resolution of issues encountered in implementing course activities through regular (weekly) collegial discussions with each other and their course faculty
- engage them collegially in the development and refinement of new courses, including learning assessment, and their faculty's educational research based on their courses

The TAs felt that they learned most when their education was firmly related to the work they were doing and where they had opportunities to contribute in a collegial manner to course development.

b) Concentrate on the professional development of STEM faculty who recognize problems in the quality of STEM education, who are curious about or interested in alternative approaches to teaching and learning, are open to change, and those who have already begun to work with new material and methods. Connect these faculty with similarly-interested colleagues in other STEM departments at the same and other local institutions, and with national disciplinary networks of innovative STEM faculty, to form mutually-supportive communities of learner-practitioners. This strategy is discussed in terms of **professional development workshops for faculty**

While the *Talking about Leaving* study was underway, faculty around the country who had also recognized many of the problems identified by students had begun to explore and share at conferences and on web-sites a body of research-based knowledge about how learning happens and strategies that would better enable it. By the time the book went to press, the first workshops for faculty wishing to learn how to teach more actively and interactively were already being held. These were largely offered by Project Kaleidoscope, organized by Jeanne Narum at the Independent Colleges Office. Project Kaleidoscope has also taken a leading role in the dissemination of materials that promote and describe scientific teaching and learning methods.

In 2000, the National Science Foundation funded the Multi-Initiative Dissemination (MID) workshops which were organized and offered by faculty who were active in the undergraduate chemistry improvement initiatives also funded by the NSF. These workshops continued to be held in regional centers until recently when government funding for the NSF's STEM education work was reduced. Faculty-led workshops have proved a highly effective and relatively inexpensive way to:

- make other faculty aware of the range of teaching methods and materials grounded in cognitive science research available to them
- see these methods modeled

- try them out in a supportive group context, and
- begin to develop their own course material and methods with help from workshop organizers and other participants. This activity continues to be supported beyond the workshop.

The faculty who organize and run the workshops are drawn from a growing pool of experienced users of scientific teaching materials and methods. They are paid only for their travel expenses. Their evaluators (Lewis & Lewis, 2006; and Burke, Greenbowe, & Gelder (2004) point to the power of the workshop method to change the participants' conceptions of teaching and learning:

> They leave the workshop sessions thinking in a different way about how effectively their students are currently learning and what modifications they might make to change that. (Burke, Greenbowe, & Gelder, 2004, p. 901)

Teaching practices are well known to be guided by faculty beliefs and conceptions of teaching (Trigwell & Prosser, 1996a, 1996b); thus genuine improvement in teaching must begin with a change in faculty thinking about teaching and learning (Ho, 2000). Lewis and Lewis (2006) found that in the ChemConnections workshops sessions, 43% of respondents were using modules by the following spring and another 13% were planning to use them in a future course. A larger proportion (57%) reported a variety of other changes in their teaching practice and 72% described a variety of gains from their experience. Lewis & Lewis also found that uptake of new teaching ideas was greater in workshops lasting two or more days than in shorter workshops. Among respondents to their follow-up surveys, the New Traditions workshop evaluators found an even higher rate of uptake (78%) of the teaching and learning strategies that they had experienced (Penberthy & Connolly, 2000). Workshops were found to stimulate faculty new to active learning to try out these strategies. The workshops also helped repeat attenders (i.e, those already experimenting to improve their use of these strategies) to deepen their knowledge and encouraged them to add other methods.

Workshops were also offered as part of the NSF's Undergraduate Faculty Enhancement (UFE) program; their evaluators (Marder et al., 2001; Sell, 1998) estimated that 81% of the 14,400 participants in the UFE workshop program made moderate or major changes to their courses, affecting an estimated 2.8 million undergraduates. When the workshops directly addressed teaching methods and provided time for participants to work on their own teaching materials, this was associated with later revision of a course.

As an evaluator for ChemConnections, I observed that the experience of teaching workshops helps active participants to build and sustain their networks of engaged STEM faculty and expands the pool of faculty with knowledge and expertise to share. An additional feature of Project Kaleidoscope solicits the engagement of senior colleagues by requiring all attending faculty to bring along two senior members of the department or institution. The capacity of workshops to engage as well as to educate, and to continually extend the networks of faculty convinced of the value of scientific teaching and learning methods, and ready to share their work with colleagues, makes them a powerful force for sustained change. Regional workshops bring together faculty from different institutions and connect them to like-minded colleagues locally and nationally. These connections are especially important in supporting faculty who lack departmental colleagues with similar educational interests. Connections are sustained by correspondence and reinforced by live encounters at conferences and other meetings. (It is notable that disciplinary conferences have developed education sections to service a growing interest in science education scholarship.) New collaborations form spontaneously, sustained by the intrinsic pleasures of working with like-minded colleagues—to build web-sites, develop new projects, produce new teaching materials, undertake research, and co-author articles and grant proposals. In short, faculty development workshops have emerged as a highly productive, cost-effective way to build a nationwide network of STEM faculty who are actively engaged in implementing the principles of scientific teaching and learning in their own courses and ready and able to share their knowledge and expertise with others.

A third set of strategies that are suggested by the evidence and arguments and that I have offered in this paper are to develop national programs:

- to promote mathematics and science teaching as a rewarding and well-rewarded profession using the resources of the media to reach both students and their families; to proactively recruit existing STEM undergraduates with an interest in teaching. Incentives might include scholarships or loan waivers, and removal of additional costs to students of additional years in education certification preparation.

- to develop and support baccalaureate programs combining STEM disciplinary degrees with concurrent educational preparation for teaching in the K-12 system. Students would need to be financially supported and mentored through to the early years as teachers (given the high loss rates in early teaching careers). My thoughts in this matter reflect those of the 2005 National Academy Report.

The NSF has sought through a number of ongoing programs (Collaboratives for Excellence in Teacher Preparation, Math and Science Partnerships, the State Systemic Initiatives, and a variety of outreach programs that engage STEM college faculty and their graduate students to work with K-12 mathematics and science teachers and students, to strengthen the disciplinary preparation of students entering programs of teacher preparation in colleges of education. These will continue to be needed as infusion of the teaching force with new teachers graduating with degrees in STEM disciplines will take time to build.

As a member of the National Visiting Committees of both the Texas CETP and the Puerto Rico Math and Science Partnership, I have observed in action the value of drawing university and college STEM faculty into partnerships with K-12 teachers and the two-way learning and respect that can develop from this. In our own evaluation of outreach programs using volunteer STEM graduate students, we found that the positive effects on graduate students working in K-12 classes in increasing their own interest in teaching and understanding of its challenges were at least as great as the impact that their classroom work had on the levels of interest in and understanding of science among their students (Laursen, Thiry & Liston, 2005; Liston, Laursen, Coates & Thiry, 2005).

However, as I am not a specialist in K-12 education, beyond these broad suggestions, I would defer to others better qualified than I to determine the details of a strategic national plan to address our urgent need for a profound improvement in the quality of our mathematics and science teaching force.

Finally, I would like to offer praise to the National Science Foundation and to the many private foundations who have moved us all forward in our understanding of the dimensions of undergraduate STEM education issues, through their support of STEM education research and program evaluation; who have led the way in soliciting and funding initiatives with enough scope to promote innovation among large numbers of STEM faculty; who have encouraged, supported and disseminated model programs; and who have been ready to grapple with difficult issues such as under-representation in STEM disciplines of women and people of color. Not all initiatives have worked well: finding effective ways to increase minority participation and persistence has proved particularly difficult. We also do not know the longer-term positive outcomes─both intended and unanticipated─of the larger programs. Five years (which is a normal funding span) is rarely enough time to develop programs to maturity and track their impact: this is one of many bodies of inquiry that it will be important to fund. It is impossible to imagine how limited would be our understanding of the issues that STEM undergraduate education faces, what strategies are valuable in addressing them, where barriers lie, and how to move forward, without the work of the NSF and the foundations.

In November, 2005, I was privileged to represent the US science education research and practitioner community at a multi-national Organization for Economic Cooperation and Development (OECD) meeting Amsterdam on issues in STEM education. It was clear that the European universities and school systems were struggling with many of the same issues as the United States in attracting, retaining, and educating to high quality their STEM undergraduates. I was struck how much further ahead the US researchers were in their knowledge and experience of how to harness cognitive science research in the service of improved classroom experiences for students. The proportion of faculty actively engaged in raising the quality of US STEM education, though constantly growing, is still a minority. However, it far exceeds the progress made by European colleagues to date in developing, testing, and disseminating research-grounded materials and methods. Since my return, I have responded to many requests from conference participants to supply details of available research publications and STEM web-site locations. Despite our (valid) concerns about the poorer performance of US students in international comparisons of K-12 mathematics and science learning, this is good news. What is now vital is that, for want of adequate funding, we do not let go of the ground we have gained by our investment in educational research, evaluation, program development and testing, and, above all, capacity-building among faculty who have the insight and the will to take change into their classrooms and labs and draw their colleagues into a shared endeavor to rebuild quality in STEM undergraduate education.

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