Crossing the Discipline Boundaries to Improve Mathematics Education

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The purpose of this paper is to indicate how changes occurring in undergraduate science and engineering education can inform and support improvement in undergraduate mathematics education. Reports and discussions on education in sessions at national and professional society meetings have common themes and findings across the various disciplines. However, there is not much exchange of information across these discipline boundaries. Similarly, visiting college campuses, one frequently finds mathematics faculty who have more in common in terms of their views and practices to improve undergraduate education with faculty in physics, for example, than colleagues in the mathematics department. This lack of communication and collaboration across discipline boundaries results in missed opportunities that would benefit mathematics departments and mathematics education.

Section I provides a brief summary of the Tulane Conference recommendations and general trends found among the various calculus reform projects. Section II provides similar information from reports on undergraduate education in engineering and physics, to focus on the disciplines participating in this workshop. Section III describes projects in undergraduate physics and engineering education that illustrate specific efforts occurring in these disciplines. Section IV provides summary observations.

Material for this paper is drawn liberally from national reports and testimony to the National Science Foundation obtained during the *Shaping the Future* hearings [10, 11].

SECTION I – Calculus Reform

The "Tulane Conference" [1], with funding from the Sloan Foundation, was held in January 1986 in conjunction with the Annual Joint Mathematics Meetings. The conference, attended by 25 invited participants, identified five general problems encountered at that time in the teaching of calculus:

- too few students successfully completing calculus;
- students performing symbolic manipulations with little understanding or ability to use calculus in subsequent courses;
- faculty feeling frustrated with poorly prepared, poorly motivated students;
- calculus being required as filter through which other disciplines culled out students but made little use of calculus in their courses;
- mathematics lagging behind other disciplines in use of technology.

The mathematics community responded by developing new texts and other materials for teaching calculus. *Assessing Calculus Reform Efforts* [12] is a report on the findings of a Mathematical Association of America study to assess the calculus reform movement. Many of these calculus reform efforts have been supported by the National Science Foundation (NSF) through the NSF Calculus Program and other programs at NSF [4]. The materials offer a variety of approaches to teaching and learning calculus, reaching a broader student audience. Topics are presented through

several representations; for example, graphical, numerical, symbolic, and written or verbal description. The changes in instructional practice include introduction - or increased use - of technology, modeling and applications, collaborative learning, student projects, student writing and oral presentations.

SECTION II – Reports From Other Disciplines

During this same period of time, other disciplines have been reconsidering how their subjects are taught. As the following examples illustrate, the concerns and recommendations for improvement parallel those in the mathematics community and, in particular, the calculus reform movement.

Engineering

NSF sponsored a workshop in June 1994, engaging 65 participants that represented engineering faculty, professional societies, industry, and students. The proceedings of that conference comprise the report *Restructuring Engineering Education: A Focus on Change* [8].
Concerns raised at the workshop included:

- classes typically taught in large lecture settings;
- problem assignments and assessments are highly structured;
- lack of research base in teaching and learning;
- lack of attention to different student career goals.

Proposed is creation of learning environments that include:

- active, collaborative learning;
- use of modules;
- research, development, and practical experience for undergraduates;
- learning-by-doing, the norm in professional fields;
- increased integration of science, mathematics, and engineering sub-discipline content;
- recognition of different backgrounds and career goals of students;
- rigorous educational research base in teaching and learning;
- appreciation for the complexities of physical devices and structures.

In terms of content, the workshop concluded that it is impossible to define an engineering curriculum applicable at all institutions. Each school needs to consider its own constituents and diversity of programs should be encouraged.

This flexibility in developing engineering programs is also reflected in the revised criteria used to accredit engineering programs by the Accreditation Board for Engineering and Technology, Inc. (ABET). Engineering Criteria 2000 [2] was approved by the ABET Board of Directors for a two-year comment period that began in January 1996. A phased-in implementation began with the 1998/1999 visit cycle, with full implementation of the Criteria 2000 in Fall 2001. The programs are evaluated based on student outcomes with specific course requirements not stated to the extent done so in past years. Evaluation evidence that may be used includes, for example, student portfolios, including design projects; nationally normed subject content examinations; alumni surveys that document professional accomplishments and career development activities; employer surveys; and placement data of graduates.

In the new criteria, engineering programs are expected to demonstrate that their graduates have the following capabilities:

- ability to apply knowledge of mathematics, science, and engineering;
- ability to design and conduct experiments, as well as to analyze and interpret data;
- ability to design a system, component, or process to meet desired needs;
- ability to function on multi-disciplinary teams;
- ability to identify, formulate, and solve engineering problems;
- understanding of professional and ethical responsibility;
- ability to communicate effectively;
- broad education necessary to understand the impact of engineering solutions in a global/societal context;
- recognition of the need for and an ability to engage in life-long learning;
- knowledge of contemporary issues;
- ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

The changes in the ABET evaluation criteria - and the consequent changes in engineering education --- potentially could have a significant impact on mathematics departments. As indicated earlier, the new criteria are based on expected student outcomes, rather than on a checklist of courses. This presents an opportunity for mathematics departments to work with the engineering departments toward the outcomes-based criteria. However, the new criteria also present the danger of losing the teaching of courses for those departments that do not do so.

Physics

There is a growing group of individuals conducting discipline-based research in teaching and learning in physics. The paper *Resource Letter on Physics Education Research* [6] provides an annotated compilation of over 200 references, primarily focused on postsecondary education. Many of the references are empirical studies that consider student understanding of a specific topic. *Teaching Physics: Figuring Out What Works* [7] is an example of a more general paper. This paper poses three questions: what is involved in understanding physics? what do students bring to physics classes? how do students respond to what they are taught? Among other findings, the paper reports results from a study comparing three educational environments: traditional (large lectures with small group recitations and laboratories), tutorials (including student group work on research based worksheets), and Workshop Physics (lectures, recitations, and laboratories combined into lab-based sessions)

A large body of research involves use of a multiple-choice diagnostic test, the Force Concept Inventory (FCI) [5]. FCI is a 29-question test that assesses student understanding of concepts in mechanics. Studies [e.g., 7] reported in the literature show that student performance on FCI does not necessarily improve with traditionally taught classes; in fact, student performance actually appears to have deteriorated. In addition, students appeared to deteriorate with traditional instruction in general areas such as learning independently, linking physics with reality and mathematics, and understanding concepts. An extensive study [3] conducted in a variety of school settings concluded that students in interactive classes consistently scored better on diagnostic tests than students in traditionally taught classes.

Testimony given during the hearings for *Shaping the Future* [13] reported that "we know beyond any reasonable doubt" that engaging undergraduate students in active learning and active research,

in close contact with faculty and other students, encourages students of all kinds to continue toward a career in science. Students are engaged in active learning through several means:

- classroom instruction that keeps students active;
- early participation in research;
- appropriate use of technology – for example, interconnected computers provide focus for small group discussions; spreadsheets provide means for numerical computation; digital video processing provides means to study realistic applications.

Concern was expressed that 1) computer simulations of experiments easily conducted in laboratory and
2) computer-aided instruction as was traditionally implemented isolate students and do not have desired outcomes. Also, the demand for coverage of material too often outweighs the demand for conceptual understanding and true learning.

SECTION III – Examples From Other Disciplines

The following are a few projects that have recently been funded by NSF in engineering and physics that illustrate in more specific terms some of the changes occurring in other disciplines.

- The University of Florida is developing a real-time interactive flight test program. The program allows participants to perform airborne experiments, with data reduction and analysis in real-time on board the aircraft. Videos and other sensor data from the aircraft are sent to classrooms via video-conferencing, so that the classes may actively participate in a real-time flight test.

- Daytona Beach Community College is creating a new instructional environment for introductory courses in electronics, computer-aided design, civil engineering, and computer programming. The objective of the project is to develop a virtual classroom environment through which students can access course materials and interact with other students and faculty.

- The conception, production, evaluation, and dissemination of a series of interactive modules for the teaching and learning of fluid mechanics in science and engineering is being developed jointly by Stanford University, MIT, and the University of Illinois. The modules focus on fundamentals of design but could be used in curricula of other disciplines. The primary objectives are to enhance student problem solving, intuition about complex flow phenomena, and retention of knowledge.

- A microcomputer-based laboratory at the University of Maine, Farmington is being used to introduce an inquiry-based curriculum into the general physics sequence. The student population of the course is approximately half science majors and half secondary education majors. In this project there is a particular focus on the pre-service teachers in the course. This focus consists of having "alumni" of the general physics sequence return as peer instructors in both the workshop physics course and the conceptual physics course designed for non-majors. This is being done by having the physics and secondary education faculty work together to affect program changes that would require the secondary education students to have this teaching experience as part of the degree requirements in education. The goals are to further improve the

understanding of physics of these science teachers-to-be and to give them some practical experience with an inquiry-based physics curriculum.

- A project at Carnegie-Mellon University is developing a calculus-based introductory textbook on mechanics and thermal physics. The text presents ideas previously treated separately as an integrated whole, emphasizing atomic-level description, analysis, and modeling.

SECTION IV – Summary Observations

The previous sections serve to illustrate common concerns and recommendations for undergraduate education engineering, mathematics, and physics. In summary, the following major areas are identified:

- *Course Emphasis*. Current courses tend to emphasize manipulative skills, routine experiments, or cookbook techniques rather than student understanding and competence in the subject. Course design, including student testing, should place more emphasis on understanding of concepts, scientific method, and relevance in a broader context. The curriculum in general should reach a wider spectrum of students in terms of backgrounds, interests, and career goals.

- *Educational Practices*. In general, there is too much reliance on lecture, routine student exercises and laboratories, and examinations designed primarily to minimize student and faculty time. The reports recommend that faculty increase their use of collaborative learning, discovery based student activities and student research, projects, writing assignments, oral presentations, and other practices that provide more engaging and effective education.

- *Computer Technology*. Computer technology can be used, for example, to engage students in discovery, provide access to large databases, gather information, and collaborate over large distances.

- *Content.* In general, these reports conclude that courses try to cover too much material, at the expense of a sufficiently deep treatment of the subject. It is recommended that courses include fewer topics for which deeper student understanding would be possible and expected.

- *Research Based Educational Decisions*. Discipline based research in teaching and learning should provide a scholarly basis for informed educational decisions. This research is providing insights into what students actually learn and what educational practices are effective for improved learning.

At disciplinary society meetings across the country, faculty discuss ways to improve undergraduate education. Although these meetings are held within the separate disciplines, the issues, concerns, and recommendations have much common ground across the disciplines. These faculty return to their home institutions and too often find themselves working in isolation. Colleagues in their own discipline may not be receptive, and they do not communicate across the discipline and department boundaries.

The benefits of these interactions across discipline lines are multiple. Students benefit in having both content and pedagogical approaches, including uses of technology, reinforced in different courses and discipline settings. The content in mathematics courses can be enriched through applications relevant to the other courses that students take. Faculty implementing similar strategies in different disciplines can benefit through collaboration. The institutional support possible through having a critical mass of faculty with common interests is also not realized. Moreover, the mathematics department, in general, can be better positioned as central to the institutional mission to provide undergraduate education.

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