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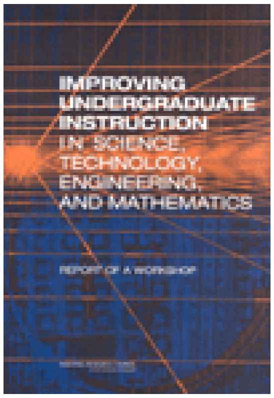

**Improving Undergraduate Instruction in Science, Technology, Engineering, and Mathematics: Report of a Workshop**

Richard A. McCray, Robert L. DeHaan, and Julie Anne Schuck, Editors, Steering Committee on Criteria and Benchmarks for Increased Learning from Undergraduate STEM Instruction, Committee on Undergraduate Science Education, National Research Council

ISBN: 0-309-50968-8, 176 pages, 8 1/2 x 11, (2003)

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# IMPROVING UNDERGRADUATE INSTRUCTION IN SCIENCE, TECHNOLOGY, ENGINEERING, AND MATHEMATICS

## REPORT OF A WORKSHOP

Steering Committee on Criteria and Benchmarks for Increased Learning from Undergraduate STEM Instruction

Richard A. McCray, Robert L. DeHaan, and Julie Anne Schuck, Editors

Committee on Undergraduate Science Education
Center for Education
Division of Behavioral and Social Sciences and Education

NATIONAL RESEARCH COUNCIL
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THE NATIONAL ACADEMIES PRESS
Washington, D.C.
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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract/Grant No. ESI-0102582 between the National Academy of Sciences and National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

**Library of Congress Cataloging-in-Publication Data**

Improving undergraduate instruction in science, technology, engineering, and mathematics : report of a workshop / Steering Committee on Criteria and Benchmarks for Increased Learning from Undergraduate STEM Instruction, Committee on Undergraduate Science Education, Center for Education, Division of Behavioral and Social Sciences and Education ; Richard A. McCray, Robert L. DeHaan, and Julie Anne Schuck, editors.
p. cm.
Includes bibliographical references.
ISBN 0-309-08929-8 (pbk.)
1. Science—Study and teaching (Higher)—United States—Evaluation—Congresses. 2. Technical education—United States—Evaluation—Congresses. 3. Engineering—Study and teaching (Higher)—United States—Evaluation—Congresses. 4. Mathematics—Study and teaching (Higher)—United States—Evaluation—Congresses. I. McCray, Richard. II. DeHaan, Robert L. (Robert Lawrence), 1930- III. Schuck, Julie Anne. IV. National Research Council (U.S.). Steering Committee on Criteria and Benchmarks for Increased Learning from Undergraduate STEM Instruction.
Q183.3.A1I493 2003
507′.1′173—dc21
2003009499
ISBN 0-309-50968-8 (PDF)

Additional copies of this report are available from The National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America.

Suggested citation: National Research Council. (2003). *Improving undergraduate instruction in science, technology, engineering, and mathematics: Report of a workshop*. Steering Committee on Criteria and Benchmarks for Increased Learning from Undergraduate STEM Instruction. Richard A. McCray, Robert DeHaan, and Julie Anne Schuck (Eds). Committee on Undergraduate Science Education, Center for Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

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# STEERING COMMITTEE ON CRITERIA AND BENCHMARKS FOR INCREASED LEARNING FROM UNDERGRADUATE STEM INSTRUCTION (2003)

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# Preface

The Committee on Undergraduate Science Education (CUSE) has been an integral component of the Center for Education (CFE) of the National Research Council (NRC) since it was established in 1993. Charged by the NRC with responsibility for seeking ways to improve scientific literacy for all undergraduates, this standing committee has worked to identify, develop, and promote implementation of postsecondary programs that enrich students' understanding and comprehension of science, and that enhance the scientific reasoning skills that they need for continued learning and success as scientifically literate citizens.

To date, CUSE has been involved with several reports, among them *Science Teaching Reconsidered: A Handbook* (NRC, 1997); *Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology* (NRC, 1999); and most recently *Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics* (NRC, 2003). *Science Teaching Reconsidered* was meant as a practical handbook designed for college teachers who want to explore new ways to enhance student learning. It drew on the current knowledge of both teachers and learning scientists to inform college instructors teaching undergraduate science courses. The 1999 report presents six vision statements for improving undergraduate education in science, technology, engineering, and mathematics (STEM) and multiple strategies for academic officers, faculty members, and departments to implement these visions. Vision two of that report, for example, calls for the development of introductory college courses that would present content information in ways that engage undergraduates in exploring the fundamental and unifying concepts and processes of science, emphasizing real problems, applications to related areas of knowledge, and the evolving processes of scientific thought and inquiry. The more recent report (NRC, 2003) recommends importantly that evidence of student learning be used as a benchmark for evaluating teaching effectiveness. That report also stresses the utility of ongoing self-study and evaluation by STEM departments and suggests a series of questions for departments to use in this process.

In 2002, with new leadership and largely new membership, CUSE set about to build upon this background by convening a 2-day workshop covering instruction in the four major scientific disciplines (biology, chemistry, physics, geosciences) with the primary goal of developing criteria and benchmarks for evaluating undergraduate STEM program effectiveness. According to the charge from the NRC, the resulting workshop report was to include descriptions of general learning goals that could be refined by any department for each discipline, and a framework for developing instruments with which to assess achievement of those goals, uses of evidence, programmatic costs, and other criteria, as well as descriptions of selected exemplary programs.

This report is the product of that gathering of some fifty expert participants in fields ranging from the scientific disciplines to educational psychology and sociology, national policy, information technology, and education research. Focusing on the question: "how is undergraduate instruction to be assessed?" panel members and discussants were required to ask what constitutes effective instruction. On the logic that effective instruction is that which maximizes student learning of specified learning outcomes, attendees were asked to consider a diverse set of goals: how to establish worthy learning objectives, how to take into consideration student pre-conceptions about a subject, what teaching strategies elicit comprehension rather than memorization, the characteristics of effective teachers, and the organizational and incentive structures of departments and institutions that promote effective instruction.

The committee sees this workshop and resulting report as timely efforts. Pressures from within and beyond the academic community (business and industry, state legislatures, federal legislation) are mounting to improve student learning and to increase institutional accountability for that learning. Especially in lower division courses, expectations are that departments will enhance learning by a new emphasis on teaching with curriculum revision and improved instruction. In this report, the committee explores many of the questions raised by those expectations.

We would like to thank the workshop

participants, listed in Appendix D, who gave life to this gathering. The frankness and thoughtfulness of their contributions, both verbal and written, added greatly to the value of the vigorous discussions that characterized the event. Within the NRC, the committee wishes to thank Julie Anne Schuck, CUSE research associate, for her skillful writing and dedicated editorial work on the report, Mary Ann Kasper, senior program assistant for her able logistical coordination of the workshop and committee meetings, and Kirsten Sampson Snyder, for guiding us through the intricacies of the review and publication process. The committee extends its deep appreciation to Jay Labov, deputy director of CFE, for sharing his experience and perspective on this project from its inception.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: Deborah Allen, Department of Biological Sciences, University of Delaware; Robert J. Beichner, Department of Physics, North Carolina State University; Thomas R. Berger, Department of Mathematics, Colby College, Waterville, ME; Jerry P. Gollub, Natural Sciences and Physics, Haverford College, Haverford, PA; David Gosser, Department of Chemistry, The City College of CUNY, New York, NY; and Lillian Tong, Center for Biology Education, University of Wisconsin-Madison.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the final draft of the report before its release. The review of this report was overseen by Melvin D. George, President Emeritus, University of Missouri, Columbia. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Richard McCray, *Chair*
Robert L. DeHaan, *Director*
Committee on
Undergraduate Science Education

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# 1

# Introduction

## RATIONALE

What students learn and how they are taught in college science, technology, engineering, and mathematics (STEM) courses are issues that have occupied educators for many years (Dwyer, 1972; Arons, 1983) and have been the focus of previous National Research Council (NRC) studies (e.g., 1997, 1999, 2003). These studies point to the growing body of empirical research showing that learning can be enhanced when college instructors incorporate teaching strategies that are student-centered, interactive, and structured around clearly stated measurable learning outcomes.

A crucial question, then, is why introductory science courses in many colleges and universities still rely primarily on lectures and recipe-based laboratory sessions where students memorize facts and concepts, but have little opportunity for reflection, discussion, or testing of ideas. Do instructors have readily available information about instructional techniques shown to be more effective in eliciting students' understanding and in helping them develop useful knowledge? Are they afforded opportunities to learn about alternative teaching strategies? Do barriers and disincentives at the institutional/departmental levels discourage faculty from adopting such strategies?

These were some of the questions that prompted the NRC's Committee on Undergraduate Science Education (CUSE) to organize the present workshop. A steering committee (biographical sketches in Appendix E) was established to develop a workshop with invited presenters and small working groups that were asked to explore three related issues: (1) how appropriate measures of undergraduate learning in STEM courses might be developed; (2) how such measures might be organized into a framework of criteria and benchmarks to assess instruction; and (3) how departments and institutions of higher learning might use such a framework to assess their STEM programs and to promote ongoing improvements.

Workshop participants would focus on four questions regarding undergraduate STEM education at the classroom, departmental, and institutional level: (a) what characteristics and indicators should be included in a comprehensive evaluation instrument that could serve as the basis for recognizing exemplary STEM courses and academic programs; (b) what are the desired student outcomes of such STEM courses that can indicate course effectiveness; (c) what qualities of organization, governance, and incentive structures can be identified at the departmental and institutional levels that promote quality STEM education; and (d) how can such qualities be used as the basis for creating indicators and benchmarks for the evaluation of institutions and departments?

To sharpen and focus these questions, breakout groups at the workshop were asked to define "appropriate measures of undergraduate learning" by developing a list of desired student learning outcomes for each science discipline. The logic here was that student success in achieving defined learning outcomes could serve as an indicator of the effectiveness of a particular course or an instructional approach. Further, still using student learning outcomes as a criterion of success, workshop participants were challenged to identify characteristics and indicators that should be included in a comprehensive evaluation instrument or framework for recognizing a hypothetical "exemplary" STEM course. To investigate how departments and institutions of higher learning might use such a framework to assess their STEM programs, workshop participants were instructed to identify qualities of organization, governance, and incentive structures at the departmental and institutional levels that promote quality STEM education, and to consider how such qualities could be used to create a set of indicators and benchmarks for the evaluation of institutions and departments.

As an initial step in thinking about appropriate measures of undergraduate learning in STEM disciplines, workshop participants were asked first to identify a few "exemplary" programs that were known by reputation to be effective in achieving desired learning outcomes. Participants then outlined characteristics that would enable an observer to classify these programs as effective. These characteristics, which are summarized in Chapter 3, could be included in a comprehensive evaluation instrument that would serve as the basis for assessing STEM courses and academic programs. Broken into groups by discipline (physics, chemistry, life sciences, geosciences), the participants were then asked to enumerate the desired learning outcomes that indicate course effectiveness. The groups chose not to emphasize any content-specific lists of outcomes, but instead focused on the cross-disciplinary outcomes. The reported outcomes were remarkably similar across groups. These outcomes are summarized in Chapter 2. The process of developing appropriate learning outcomes as well as measures, which includes designating working teams, asking appropriate questions, and collaborating to answer these questions, was described by several workshop presenters (see Chapters 2 and 4) and exemplified by participants during the workshop.

The organization of a framework of criteria and benchmarks, as specified in issue 2, was not accomplished at the workshop. A recent NRC report *Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics* (2003) points out that development of a universal evaluation instrument is difficult if not impossible since academic institutions vary greatly in mission and demographics. The workshop participants represented a variety of institutions and found reaching consensus on a set of criteria suitable for each institution difficult. Readers of this report may choose to organize the characteristics of effective programs and instructional strategies outlined in Chapter 3 into a framework of criteria and benchmarks suitable for their own institutions.

Instead of deliberating on how institutions and departments would use such a framework (issue 3), workshop participants focused their discussions on the personality traits of faculty as well as the qualities of organization, governance, and incentive structures at departmental and institutional levels that promote effective STEM education. They also discussed institutional characteristics that are barriers to the implementation of effective instruction. These qualities, which are summarized in Chapter 4, can serve as the basis for creating indicators and benchmarks for the evaluation of institutions and departments. Several presenters described approaches that faculty, departments, and institutions can take to develop and incorporate qualities that promote quality STEM education (see Chapter 4).

Throughout the workshop, participants voiced many concerns that have been raised in earlier studies; however, they also presented new efforts, arguments, and evidence. Buttressed by recent studies, this report documents more convincingly than earlier reviews that instruction based primarily on lectures may be useful for transferring factual information but is much less effective at achieving more complex conceptual learning outcomes. It provides a new approach to promoting effective STEM instruction by examining the personality traits of faculty—those characteristics that allow faculty to respond to institutional/departmental changes as well as those that directly or indirectly affect the culture of the department and institution. The report advances the argument for increased collaboration among faculty and administrators and provides illustrative examples of effective collaborative efforts.

The rest of this section provides background to the body of research supporting the concerns of the steering committee and raises additional questions that prompted the development of this workshop.

## Student Learning Outcomes

Starting with *A Nation at Risk* (National Center for Excellence in Education, 1983), with its "Imperative for Educational Reform," hundreds of reports—at the rate of almost one per week according to Tobias (1992)—by national associations, blue-ribbon committees, commissions, and accrediting boards have produced visions of improved STEM education. These new visions, remarkable in their agreement, focus less on what instructors teach and more on what students learn and are able to do with their new knowledge. They also focus less on terms and facts that students memorize and more on students' conceptual understanding and their ability to apply knowledge in novel contexts. For higher education, a primary objective is that "all undergraduates have learning experiences that motivate them to persist in their studies and consider careers in these fields" (Project Kaleidoscope, 2002, p. 1). The requirements of the Accreditation Board for Engineering and Technology (2002), for example, state that students should gain an ability "to apply knowledge of mathematics, science, and engineering; to design and conduct experiments as well as to analyze and interpret data; to function on multidisciplinary teams; and to communicate effectively."

The American Psychological Association standards for undergraduate education in that discipline expect that students "will understand and apply basic research methods…including research design, data analysis, and interpretation; will respect and use critical and creative thinking, skeptical inquiry and when possible the scientific approach to solve problems…; [and] will be able to communicate effectively in a variety of formats" (2002).

A panel convened by Sigma Xi, The

Scientific Research Society, concluded that introductory STEM courses should enable students "to understand science, mathematics and engineering as processes of investigation—as ways of knowing; to have hands-on experience with investigations and to discover the joy and satisfaction of discovery; to understand the powers and limitations of science mathematics and engineering; [and]…to understand the synergisms among science disciplines and the synergisms among science, mathematics and engineering" (1990, p. 9).

With each passing year, the need for faculty to define and learn how to elicit appropriate learning outcomes among students in undergraduate STEM courses has gained in importance. The percentage of high school graduates who choose to enter college has increased dramatically in the past two decades—from about 50 percent to 66 percent between 1980 and 1998 (National Center for Education Statistics [NCES], 2000). During those same years the number of fall semester enrollees represented by minorities increased from 16.5 percent to 26.6 percent (Snyder, 2001, pp. 295–296).

Spurred in part by an increasing "college wage premium" that promises far higher earnings from degrees in specific fields (NCES, 2000, p. 144), many of these students declare their intentions to pursue an aspect of science or technology in their postsecondary education. Between 1970 and 1998 enrollment in computer and information sciences as well as agriculture and health-related sciences rose by an average of 250 percent (although physical sciences and mathematics actually lost students over that period) (Snyder, 2001, pp. 295–296). As recently noted in a related NRC report (Hudson, 2002, p. 37), "In general, the shift in the past three decades appears to be away from the humanities and hard [physical] sciences toward business, technical, and health fields." These students, those still selecting science and technology and many who pursue fields outside of science or technology, are required to take college science courses at the introductory level.

The rise in number and diversity of students intensifies the need for faculty to see introductory courses for both majors and nonmajors as a critical part of the undergraduate curriculum. Such courses can serve not only as vehicles for providing students with the facts and concepts of science but also as opportunities to develop their understanding and appreciation of the processes of science as well as cognitive skills such as posing and solving problems, making sense of data, and reasoning and arguing from evidence—all of which are crucial to decision making no matter what field of endeavor a student enters after graduation. Introductory science courses can also be designed to properly prepare those who wish to continue in science as a profession, those who will affect the science education of future students as K–12 teachers, administrators, or policy makers, and those who desire to be informed citizens in this increasingly scientific and technological world.

Unfortunately, this vital education in science is reaching too few of today's undergraduates (Seymour and Hewitt, 1997). Many students leave science-rich fields for other areas of interest after their first lower-division college science courses or drop out of higher education completely. According to Seymour and Hewitt's (1997) comprehensive study, a loss of over half of the students who enter college intending to pursue majors in the natural sciences occurs within two years of taking their first college science or mathematics classes, a problem of wastage that affects both minority and majority students. Students reported being dissatisfied with what they perceived as poor teaching and other negative experiences in "weed-out" science courses. Frequent complaints were heard about courses and textbooks that are filled with facts that students are expected to memorize with little opportunity for conceptual development, and tests that only assess students' abilities to remember such facts from recent lectures and chapters. An important result of this shift away from science and math courses during the upper division undergraduate years is a striking decline in students choosing advanced or graduate courses leading to STEM professions. From 1993 to 2000, enrollment in STEM graduate programs decreased by more than 14 percent, with three areas, math (32 percent), engineering (25 percent), and the physical sciences (18 percent) suffering the most prominent losses (Zumeta and Raveling, 2003, p. 37).

## Effective Instruction

Reacting to reports indicating that new knowledge is assimilated through interaction with existing knowledge (summarized in NRC, 2000), workshop participants considered how an instructor might be encouraged to provide opportunities for students to become actively involved in creating new understandings. Recent evidence suggests that students who sit passively in lectures for an entire course may fail to replace their prior misconceptions with new knowledge; the conceptual difficulties they have when they enter a course are likely to persist if instruction does not address their difficulties specifically (King, 1994; Mestre, 1994; Loverude et al., 2002; Marchese, 2002). For many students the traditional didactic lecture, when applied as the primary instructional method in science courses, fails to provide opportunities for integrating new and old knowledge. Lectures may lead to memorization of factual information but often do not succeed well in eliciting comprehension of complex concepts (Terenzini and Pascarella, 1994; Honan, 2002; Loverude, Kautz, and Heron, 2002).

Despite such evidence, according to a broad survey of 123 research-intensive (Research I and II) universities nationwide by The Reinvention Center at Stony Brook (2001), only about 20 percent of R-I and R-II universities provide opportunities for active learning or real-world problem solving for their students in a substantial number of introductory science courses. On a majority of campuses the instructor as a didactic lecturer remains typical practice in STEM courses. As noted by Alison King (1994), "Much of what transpires in today's college classrooms is based on the outdated transmission model of teaching and learning: the professor lectures and the students take notes, read the text, memorize the material, and regurgitate it later on an exam" (p. 15).

## Role of Academic Departments in Improving Teaching Effectiveness

The personal experiences of a number of workshop participants confirmed that the current culture of many science and engineering departments is one that values the productive investigator more than the effective teacher. In an effort to counteract that emphasis, the NRC report *Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology* (1999) presents six vision statements and multiple strategies for implementing these visions. The vision statements are designed to assist academic officers, faculty members, and departments in their efforts to improve STEM education.

Vision two of that report calls for the development of introductory college courses that would present content information in ways that engage undergraduates in exploring the fundamental and unifying concepts and processes of science. These courses would emphasize real problems, applications to related areas of knowledge, and the evolving processes of scientific thought and inquiry. Vision three calls on all colleges and universities to continually and systematically evaluate the efficacy of their STEM courses and programs. The NRC report *Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics* (2003) recommends that evidence of student learning be used as a benchmark for evaluating teaching effectiveness. That report also stresses the utility of ongoing self-study and evaluation by STEM departments and suggests a series of questions for departments to use in this process.

## OBJECTIVES AND ORGANIZATION OF THE PROJECT

Against the background outlined in the preceding paragraphs, CUSE established a steering committee to develop the present workshop. Eleven experts in STEM education and/or institutional reform accepted invitations to present at the workshop as a means of informing the committee and catalyzing discussion among attendees. Additional experts were assigned as facilitators to two breakout sessions. The breakout sessions were planned to capture the interactions among the attendees, who brought with them much relevant experience. The facilitators, two per group, were asked to keep their groups focused on the questions, to make sure that everyone's voice was heard, to promote a supportive atmosphere that evoked creative ideas without overorganizing the conversation, and to record the discussions in order to report a summary during the plenary session. Additional authorities on STEM education were sent workshop announcements and encouraged to attend. In addition, three of the presenters were asked to prepare short papers in advance of the workshop to further discussion of the guiding questions, and were then asked to modify and expand their papers based upon the discussion at the workshop (revised papers are provided in Appendix A).

The workshop was held in Washington, D.C., November 19–20, 2002, at the National Academies. (The Workshop Agenda can be found in Appendix C.) Commissioned papers were distributed to registered participants within the week before the workshop. Fifty-one invited participants, including presenters and facilitators, attended the workshop along with NRC staff and other interested parties. Names and institutional affiliations of registered participants and steering committee members are listed in Appendix D.

## ORGANIZATION OF THE REPORT

This report is based on the presentations and papers commissioned for the workshop and on the discussion that emerged from the workshop itself. The commissioned papers as revised by the authors following the workshop are reprinted intact in Appendix A, so they are not summarized in the report. However, authors also formally presented material found in their papers as part of the plenary sessions, and those aspects of the papers appear in that context in the following chapters.

Participants in this workshop were charged with examining student learning outcomes in the sciences, exemplary instructional practices, and the barriers as well as the enablers to instructional reform at the institutional level. Through presentations by plenary speakers and the discussions that followed, reports from breakout sessions, and general discussions throughout the workshop, major themes emerged. In this report, a summary of the workshop presentations and subsequent discussion, participants' statements, and the resulting themes are organized around the workshop's guiding questions into three related areas: identifying desired learning outcomes, evaluating effective instruction, and promoting effective instruction at institutional and departmental levels.

The following chapters focus on the four guiding questions (a-d) regarding undergraduate STEM education presented at the beginning of this chapter. Chapter 2 addresses question b—what are the desired student outcomes of such STEM courses that can indicate course effectiveness—by examining the process of developing such learning outcomes. It outlines some of those outcomes defined as most important by the workshop participants. Chapter 3 identifies characteristics and indicators that can be included in a comprehensive evaluation instrument for rating exemplary STEM instructional programs (question a) and tools for assessing the quality of faculty instruction. Chapter 4 examines characteristics of organization, governance, and incentive structures identified at the personal, departmental, and institutional levels that promote quality STEM education (question c). It also considers qualities that serve as barriers to implementation of effective instruction and describes approaches to promote such instruction at the institutional/departmental level. Chapter 5 summarizes the general discussion that occurred at the end of the workshop, highlighting qualities that could be used as the basis for creating indicators and benchmarks for the evaluation of institutions and departments (question d). In an Epilogue (Chapter 6), overriding concerns that participants voiced repeatedly serve as a summary of the major issues in the report.

References to specific programs and initiatives that were discussed by workshop participants are included throughout this report. These programs are cited for information purposes only; such citation does not imply endorsement by the NRC.

# 2

# Identifying Desired Student Learning Outcomes

This chapter considers evidence concerning how to develop and define student learning outcomes. In the workshop, participants were asked to identify outcomes that would confirm a program's effectiveness. We define effective programs here as those that are able to elicit and measure students' conceptual understanding and their ability to transfer knowledge to new contexts. In an opening presentation, Barbara Baumstark, Georgia State University (GSU), outlined the process for developing learning outcomes. First, an academic team, including administrators and faculty, needs to be designated. Second, the team asks appropriate questions and solicits input from other peers and instructors. Third, the team collaborates to write down their proposed learning outcomes. The workshop participants exemplified this process in their own effort to identify learning outcomes that would indicate program effectiveness. The working groups, segregated by discipline, were unable in the time allotted to define lists of content-specific outcomes. But they came to broad agreement on a set of important cross-disciplinary skills and competencies as learning outcomes for introductory science courses.

The workshop participants drew attention to challenges in achieving these outcomes. Instruction that relies solely on lectures and recipe-based labs would need to change to achieve the proposed learning outcomes. Students are often resistant to changes in instructional approaches. Many have become accustomed to memorizing terms and facts and receiving information from the instructor in a one-way fashion and have developed strategies to succeed in such courses. These strategies often fail in courses with more learner-centered forms of instruction. A second challenge lies with students' preconceptions, which are unlikely to change unless specifically addressed by instructional strategies. Persistent preconceptions often limit student's conceptual understanding and ability to apply new knowledge appropriately to new contexts.

In the pages below an expanded summary of Baumstark's presentation, the learning outcomes proposed by workshop participants, as well as additional ideas and cautions put forward by participants during plenary discussions, are detailed.

## STUDENT LEARNING OUTCOMES

When a conscientious college instructor designs a course for undergraduates, the usual questions are: "What topics do I need to cover for these particular students? What are the prerequisites for the course, and do they serve as prerequisites for other courses? What textbook or materials should I use? Should the course include a lab experience? If so, to what extent is it possible to correlate the material covered in the lecture with that in the lab?"

Rarely, however, is much thought given to answering two other crucial questions: "What, explicitly, do I want the students to know and be able to do at the end of the course?" and "How will I assess whether they have achieved those learning outcomes?" Yet answers to the latter questions are critical in determining what is taught and how it is taught (Wiggins and McTighe, 1998; Huba and Freed, 2000; NRC, 2001). This is not a new or radical view. In a now classical text on instructional methods, Tyler (1949) describes the logic of starting with learning outcomes: "Educational objectives become the criteria by which materials are selected, content is outlined, instructional procedures are developed, and texts and examinations are prepared…[the objectives] indicate the kinds of changes in the student to be brought about so that instructional activities can be planned and developed in a way likely to attain these objectives" (pp. 1, 45).

### The Process of Developing Learning Outcomes

*Barbara Baumstark, Georgia State University (GSU)*

What then are the processes by which a college instructor develops a series of learning outcomes for a course? In her workshop presentation *Wandering Through the World of Standards*, Baumstark described her experiences with Quality in Undergraduate Education (QUE) (http://www.pewundergradforum.org/project9.html).

### *Designating the Academic Team*

A national project, QUE engages faculty at selected four-year public institutions and their partner two-year colleges in drafting voluntary discipline-based standards for student learning for undergraduate majors. Her university partnered with Georgia Perimeter College to develop standards to be achieved by the end of the sophomore year (Level 14) in biology and history.

### *Asking Appropriate Questions*

Baumstark's group, which developed the standards for biology, began by trying to establish its own definition of the term "standards," and soon decided that the meaning commonly used by K–12 educators was adequate: "what a student should know and be able to do." They considered whether the standards should represent *minimum* levels of competency. Realizing that the QUE effort was looking for more than minimums, they determined that their standards should not be limited to a list of content terms, but should instead comprise a mutually supportive framework of facts, concepts, thinking skills, and abilities. They wanted their standards to represent learning as a process of asking questions, drawing on one's background not only in biology but also in an array of disciplines (including perhaps history and literature), and relating new knowledge to existing knowledge. To prepare standards for Level 14, Baumstark and her colleagues solicited input from both upper and lower division instructors, asking them to describe the knowledge and skills they would like students to have before entering their upper division courses and similarly those that they wanted students to gain from their introductory classes.

In the discussion, Michael Zeilik, University of New Mexico, pointed to the need to identify the audiences of introductory science courses, which often include future scientists, students who will pursue studies outside the sciences, and preservice teachers. His concern was about how to integrate these diverse students and meet their needs in the same set of courses.

### *Writing Down the Outcomes*

Baumstark directed workshop participants to the QUE website as she pointed out that those involved with the QUE project found "the process of writing the standards [in] itself rich and stimulating." The GSU faculty agreed that three areas of learning are critical: scientific process, content, and application. As defined by Baumstark, scientific process describes students' familiarity with "the hypotheses, [experimental] techniques, and data analysis that have formed the basis for what the upper division [faculty] were going to teach [as well as] currently accepted scientific principles." Content refers to the essential knowledge base required to facilitate assimilation of new concepts; application represents the skills students develop as they apply their understanding to solve new problems or extend their investigations. Some of the standards, or "learning outcomes" as they were later called by her team, included students' demonstrations that they have developed the skills necessary for scientific inquiry, reasoning, and communication; a knowledge of the history and nature of biology; a recognition of the correlation of biology with other sciences and technology; a recognition of the personal and societal impacts of developments in biology; and the knowledge of appropriate information content to facilitate assimilation of new concepts and content in the future.

### *Discussing the Program, Not Just Individual Courses*

In her presentation, Baumstark emphasized the importance of defining desired learning outcomes for entire programs, not just individual courses. Baumstark's QUE project group had determined that by Level 14 students should have had opportunities to take ownership of a knowledge base sufficient for further study and the skills necessary to use this knowledge. By Level 16, students will have identified areas of interest within biology and become proficient in scientific process skills through a focus in these areas. To their surprise, when the group examined the current GSU biology curriculum, lower to upper division, they discovered that the scheduling of upper division specialty electives caused them to conflict with one another: students often took random electives that fit their schedules rather than selecting those that might form a coherent approach to the subfields of interest.

The group then assembled faculty in each subfield (for example, neurobiology) to identify courses they would recommend to interested students. Once these courses were classified, the GSU biology program took steps to schedule specialty electives such that those in a given subfield would not conflict with each other. By considering outcomes for a program, faculty not only identified a scheduling problem that was easy to fix, they started important conversations, developed relationships with colleagues, and learned from each other. Baumstark pointed this out in recounting her experiences: "We identified courses that we thought would be very good for our students in molecular genetics to take, and also by discussing these courses, we began to realize what the other courses had to offer. Faculty tend to be very proprietary about their courses, but when you think of it as we are all working toward a common goal,

…we would start sharing with each other. This is an example of something I found worked in my course. Maybe you can adapt it to another course."

### The Mapping of Learning Outcomes Across a Four-Year Curriculum

*Gloria Rogers, Rose-Hulman Institute of Technology*

Rogers, in her presentation outlining the process for evaluating student outcomes (see detailed presentation in Chapter 3), also stressed the importance of examining ("mapping") the entirety of the four-year curriculum in order to identify courses where students have opportunities to learn and demonstrate the desired knowledge and skills. Through such mapping, a program will be able to define and articulate what skills and knowledge a graduate of their program will have achieved in four years. It can identify within the curriculum what is already being done appropriately and where gaps persist. Through continuous mapping, feedback, and program adjustment, the faculty can demonstrate to themselves that desired outcomes are being achieved within their program. Rogers suggested that if a program takes the final step of presenting the map to students, the students would also become aware of their learning objectives and the opportunities to demonstrate the desired outcomes.

Sarah Elgin, Washington University, agreed that a program should be examined as a whole, as an interconnecting sequence of individual courses. She suggested that departments examine course prerequisites by considering the reasons for such requirements and developing a progression of learning outcomes throughout programs.

David Brakke, James Madison University, extended this idea by suggesting that institutions should seek input from their own faculty and administration about what they are trying to accomplish in the programs they offer. An inward look by college faculty and administrators (as also proposed in NRC, 2003), would lead to examination of existing policies and programs and raise appropriate questions regarding student learning outcomes. Brakke pointed to undergraduate research programs as an example of effective learning environments when conducted correctly. The compositions of and reasons for adopting undergraduate research are wide-ranging, according to Brakke. Many institutions support and include undergraduate research experiences on their campuses; however, few stop to think why they offer such programs or what larger goals they are trying to achieve.

## LEARNING OUTCOMES PROPOSED BY WORKSHOP PARTICIPANTS

Examples of desired learning outcomes were presented throughout the workshop in formal presentations and in the breakout summaries. For example, in the second breakout session, the discipline groups were assigned two tasks: to prepare a consensus list of student outcomes for the discipline and to identify conceptual and cognitive outcomes that might serve as cross-disciplinary learning goals.

### The Summaries of Breakout Groups

Paula Heron, University of Washington, and Jack Wilson, UMassOnline, summarized the discussions of the physics working group. The group identified the following learning outcomes as necessary for appreciating the nature of physics: students should recognize (1) the experimental applicability and universality of a few idealized models to a wide range of phenomena in physics and other disciplines; (2) the value of physical meanings of formal representations such as mathematical equations, diagrams, and graphs; (3) the inevitability of uncertainty in measurement; and (4) physics as an ongoing human endeavor. The group also described content appropriate for algebra- or calculus-based introductory physics courses and confirmed the agreement that already exists within physics communities on the content for these courses. Cross-disciplinary learning outcomes are described at the end of this section following the summary of discussion stemming from the work of the breakout groups.

The participants representing chemistry and those representing the geosciences combined as one working group for the second breakout session. David Brakke and Michael Zeilik summarized the discussions of this joint group. The group reported learning outcomes already developed in the chemistry department at St. Mary's College of California and through a project of the American Astronomical Society bringing together chairs of astronomy departments (Partridge and Greenstein, 2001). By examining these outcomes, the group distinguished between learning outcomes specific to particular disciplines and those appropriate to all science disciplines. Those learning outcomes traversing disciplines are described at the end of this section.

Katayoun Chamany, Eugene Lang College, and Gordon Uno, University of Oklahoma, summarized the discussions of the life sciences group. Rather than "reinventing the wheel," that group looked at learning outcomes that had already been published by previous programs and projects[1] and generated its ideas from these (the recorded outcomes are described below). They used the Summary from University of Wisconsin Forum on Teaching Biology for Breadth (see Tables 2-1 and 2-2) as a starting point for their discussion. Many members felt the content outcomes listed in this table did not have to be achieved in every introductory biology course. The group chose to focus on process goals such as those listed in the table as "Ways of Thinking." Uno noted that professionals within the life sciences argue endlessly about content. M. Patricia Morse, University of Washington, commented that since biology is continually changing, consensus about the content of introductory courses is difficult to establish. The life sciences field appears to consist of a collection of topics, according to Chamany, that exhibit a complexity that permits educators to develop a myriad of approaches to teach a particular topic, with each instructor choosing to emphasize different aspects or perspectives. Therefore, the group decided to divide learning outcomes into broad categories of content, skills, application, and epistemology.

Although workshop participants were successful at developing and defining desired learning outcomes, they did not pursue in the available time how best to measure these outcomes. Possible measurement tools include Likert scales as well as methods detailed in Rogers' booklet (2002) and listed in Chapter 3.

### The Desired Learning Outcomes

The learning outcomes identified by the breakout groups are described below. Though the groups worked independently, the outcomes were remarkably similar across the disciplinary groups, as noted by Carl Wieman, University of Colorado. While some of the desired learning outcomes expressed by workshop participants were content- or discipline-specific, the emphasis remained on the skills that transcend scientific disciplines, and those are the ones listed. After an introductory science course, students should know that:

- **Science is an evidence-based way of thinking about the natural**

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[1] The programs and projects identified included *Beyond Bio101: The Transformation of Undergraduate Biology Education* (Jarmul and Olson, 1996; Available: http://www.hhmi.org/BeyondBio101/); *BIO2010* (NRC, 2002a); Biological Sciences Curriculum Study (Available: http://www.bscs.org/); Coalition for Education in the Life Sciences (Available: http://www.wisc.edu/cels/); Quality in Undergraduate Education (Available: http://www.pewundergradforum.org/project9.html); and *Science as a Way of Knowing* (Moore, 1999).

TABLE 2-1 Question: "What, if any, might be the concepts, information, and issues that every biologically literate citizen needs to know?"

| Concept | Information | Issues |
|---|---|---|
| Evolution | Living systems change through time, resulting in diversity (process of evolution, natural selection, biodiversity) | Preservation of species |
| Interdependence and interaction | Ecological interactions (organism/organism, organism/environment) | Human population explosion, place in the biosphere, human-animal interactions |
| Basic genetics | Generations of living systems are related to each other by passing on genetic material through reproduction (molecular genetics) | Genetic engineering, nature vs. nurture |
| Cell biology | Machinery within cells and interactions between cells define the properties of living organisms | |
| Energy and matter | How living systems generate energy from their foodstuff: energy and matter is required for maintenance of the organism (metabolism) | Nutrition |
| Organization and operation in living systems | Living systems can be complex and require organization and regulation to maintain themselves (information flow, structure/function, development) | Health and disease |

SOURCE: Data from summary of reports from a total of 55 UW-Madison faculty and staff (9 small groups of 5–7) and discussion, Forum on Teaching Biology for Breadth, January 18, 1995, University of Wisconsin-Madison, Undergraduate Biology Education Committee (UBEC) and Center for Biology Education. Reprinted with permission.

**world and understanding how it operates.** A scientific viewpoint about the physical world is different than other viewpoints (for example, a religious viewpoint), in that ideas and opinions are based on observation, evidence, and theories (or models). When scientists are faced with evidence or observations that are not consistent with currently accepted models, they have to modify their models or find appropriate rationale to dismiss the evidence or observations.

- **Science is a process with rules of operation that allow our understanding of the natural world to evolve.** The process of science is ongoing. It successively revises tenta-

TABLE 2-2 Question: "What, if any, might be the ways of thinking that every biologically literate citizen needs to know?"

| Ways of Thinking | | |
|---|---|---|
| Process of science | Process of gaining and evaluating information, "thrill of the hunt," scientific method (experimental and comparative), quantitative analysis, and reasoning (inductive and deductive) | |
| Progress of science | Science changes with time, modeling, and continual revision | Patterns and trends within specific discipline |
| Critical thinking | Integration of concepts, assessment of scientific information, decision making, healthy skepticism based on reason | Link importance to everyday life and societal issues |

SOURCE: Data from summary of reports from a total of 55 UW-Madison faculty and staff (9 small groups of 5–7) and discussion, Forum on Teaching Biology for Breadth, January 18, 1995, University of Wisconsin-Madison, Undergraduate Biology Education Committee (UBEC) and Center for Biology Education. Reprinted with permission.

tive conclusions and ideas about the world. Science has not been all figured out. Scientists continue to explore the physical world and develop models about it. Students should understand how to record data, how to put together evidence and observations to create models, and how to test models. The process includes experimental methods and systematic observations as well as communication and collaboration.

- **Science is based on reproducible evidence and observations that contain uncertainties.** Uncertainty in science arises from two major sources: measurement error and nonreproducibility. Any measurement must be seen as only an approximation, because no matter how accurate a measurement of some quantity may seem, new methods will inevitably be found for measuring the same quantity with even greater precision. Also, some observations, such as astronomical events that took place in the past, are historical. These cannot be reproduced, yet they can be used to develop and revise current models.

- **The sciences are related to each other, mathematics, and everyday life.** To teach effectively, faculty need to make these connections clear and devote more attention to how their discipline uses models and concepts from other disciplines.

- **Science is driven by globalization, technology, and new instrumentation and measurement tools.** The relation between technology and science is reciprocal; developments in science produce new technologies, and these new tools allow further progress and developments in science.
- **Scientific meanings of theory and law are different than popular meanings.** Many incoming students believe that theories are speculative and laws are proven or absolute. To scientists, a theory (or model) is a way of explaining an aspect of nature and making predictions about it. After a theory has withstood many tests, it may be referred to as a law[2] (the law of gravitation, for example), but even laws are subject to revision if new evidence requires it.

After introductory science courses, students should be able to demonstrate:

- **Ability to think critically and apply knowledge to new problems.** Participants often spoke in terms of students developing a functional understanding. Functional understanding was defined as the ability to apply concepts or principles to situations that had not been previously considered.
- **Confidence in and ability to do the process of science at an introductory level.** Students should understand what constitutes an explanation and be able to construct a logical argument. They should be able to distinguish between observation and inference. They should be able to identify the data required to answer simple questions and which techniques would best gather that data.
- **Ability to design a simple experiment.** Students should be able to perform a simple experiment, analyze the results, and identify approximations and sources of uncertainty. They should develop an understanding of variables and demonstrate knowledge of instruments needed.
- **Ability to communicate with multiple representations.** Students should be able to express their ideas through equations, graphs, and diagrams and be able to describe the physical meanings of these representations.

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[2] These are the definitions verbalized by participants during the workshop. The reader should note that the NRC (1998) report *Teaching about Evolution and the Nature of Science* publishes different definitions: “Laws are generalizations that describe [how aspects of the natural world behave under stated circumstances (p. 5)], whereas theories explain [the behaviors]. Laws, like facts and theories, can change with better data. But theories do not develop into laws with the accumulation of evidence. Rather, theories are the goal of science” (p. 56).

- **Capacity to know when they do not understand.** Students need to be able to distinguish between understanding and familiarity. To do this they need to have had the experience of understanding a body of material at a deep level.

## The Outcomes as a Set of Learning Skills

Throughout the workshop, many other participants reinforced the idea that desirable outcomes should include helping students to learn how to learn, to appreciate learning for its own sake, and to develop the skills necessary to understand both when they have learned and when they do not understand.[3] Richard McCray, University of Colorado, emphasized that introductory science courses need to focus on students' learning skills in scientific reasoning and information gathering as much as on science content, and on helping students take greater responsibility for their own learning. The content in science fields is growing so rapidly that it has become virtually impossible to transmit it all.

Some students are beginning to recognize the importance of learning skills and are placing less demand on content. Katayoun Chamany recalled the survey at her institution that asked students what they needed to learn in biology to be a contributive member of society. Expecting responses regarding content, she was surprised to discover that many students thought they should learn skills to critically evaluate information and to make personal and policy decisions.

Robert Zemsky, University of Pennsylvania, whose experience is with institutional reform of medical and business schools, recognized the emphasis medical schools now place in their curricula on information transfer, to the extent that their publications speak in terms of teaching and developing skills that resemble those of librarians. New physicians are trained to know how to ask the question, how to find the answer through resources, and how to determine the appropriateness of the answer within known constraints. Such changes reflect the recognition in recent decades that the goals of education must change from teaching science to equipping students to learn science.

According to Lillian McDermott, University of Washington, these learn-

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[3] Learning scientists often refer to this ability of students to assess their own learning and what still needs to be learned as "metacognition." A large body of scholarly research has examined the development of metacognition in students and how the education process can foster its development (White and Frederickson, 2000; Klahr, Chen, and Toth, 2001).

ing skills are most effectively taught through discipline-specific examples. Agreeing with McDermott, Priscilla Laws of Dickinson College noted that her past efforts to create introductory interdisciplinary courses ended up as survey courses where students failed to learn the techniques or modes of thinking that they can transfer later to other fields. She prefers to identify key concepts in introductory physics that will be useful to both students who continue in physics and those who choose other fields.

Robert DeHaan, National Academies, added that some courses simply cover the nature or philosophy of science and are so abstracted from anything real in science that students often do not develop a functional understanding of science. He expressed concern that the importance of content within each specific discipline would decrease in the face of an emphasis on general learning skills. Brian Reiser, Northwestern University, put the workshop participants' effort into perspective: "I agree with [McDermott's] point that you are not going to get at these [learning skills] by starting [with them]. You have to bring them out of specific examples. The reason to put them on a list like this…is to remind us that we don't usually get [from the specific topic to the general learning skill]. We usually stop at making sure [students] understand…motion, theory of natural selection, or whatever."

## THE CHALLENGES TO ACHIEVING DESIRED LEARNING OUTCOMES

In his welcoming comments to the workshop participants, Bruce Alberts, President of the National Academy of Sciences, identified several barriers to instructional reform in colleges and universities. He drew attention to the problems of incoming students and the often inadequate science backgrounds they bring with them. In K–12 science courses, students are typically faced with covering every fact of each topic in a rapid didactic mode. Alberts noted that many K–12 science teachers do not have a true feel for the nature of science and have never experienced inquiry-based instruction in their own educations. Consequently their students rarely have opportunities for such experiences themselves. Many students have become accustomed to didactic teaching even though they find many lectures boring and difficult to follow.

### Students Are Accustomed to Didactic Teaching and Resistant to Change

Throughout the discussions at the workshop, participants continued to identify aspects of students' attitudes that, as a result of their educational conditioning, influence their reactions to changes in curriculum. Teaching by inquiry methods, learning through collaborative work with peers, and using continuous student feedback to adapt curriculum, all approaches cited in earlier NRC reports (1999, 2002b), represent strategies that evoke resistance in many students, according to Elaine Seymour, University of Colorado. In her presentation (see Chapter 4), Seymour further explained that since students equate learning with memorization and perceive delivery from instructors as an important source of information, they fear practices that deviate from their expectations. To offer an explanation for students' resistance to reformed instruction, McCray added that many students place responsibility for learning on teachers and may thus expect them to teach in the form of lectures. Proposing another explanation, Alan Kay, Viewpoints Research Institute, Inc., commented that the established practice of curve grading, which pits students against one another, might encourage them to resist collaboration and group learning activities.

Probing more deeply into the issue of undergraduate resistance to alternative teaching methods, Reiser argued that students may be uncomfortable about sharing ideas and participating in collaborative activities because they fear that they might not articulate the "right" answers and thought processes in front of their peers. Moreover, students tend to be suspicious of instructors who admit that they do not know the answer; many may believe teachers know all of the answers and should supply them. Reiser found this attitude of students an extension of current grading practices that encourage students to focus on the products, assignments and exams. Since exams are often graded on final answers, one would naturally seek out the "right" answers and worry less about demonstrating how one arrived at them.

### Students' Preconceptions and Prior Beliefs Affect Learning

Several workshop participants mentioned that their groups considered students' preconceptions when they were developing appropriate learning outcomes and discussed effective instructional methods. How would students' preconceptions conflict with their ability to achieve desired learning outcomes? What type of instruction or project would surprise students such that they would reconsider their previously held beliefs? For over a decade, scientists, psychologists, and science educators have researched how students learn science concepts, particularly in physics (Halloun and Hestenes, 1985; see Appendix B, this volume). They have discovered that persistent difficulties, stemming from strongly held preconceptions and beliefs that conflict with science concepts, are common and are not easily overcome by instruction. Presenting the correct information, either orally or in written form, is seldom effective in achieving desired learning outcomes (Minstrell, 1989; Mestre, 1994; NRC, 2003). This evidence has shown that to be effective, instruction must directly confront and deliberately address students' preconceptions and difficulties. Such instructional methods are discussed in Chapter 3.

## SUMMARY

The following is a summary of the major ideas voiced by workshop participants regarding how to define desired learning outcomes. An essential first step for faculty in preparing any program is to identify explicit learning outcomes—what students should know and be able to do at the end of each course or instructional unit and the program. Clearly defined learning outcomes become the criteria by which to select materials, make decisions about content, develop instructional procedures, and prepare learning assessments. Educational value is gained by sharing learning outcomes with students so they become aware of and can take ownership of specific learning objectives. Learning outcomes should not be limited to a list of content terms, but should comprise a mutually supportive framework of facts, central concepts, reasoning skills, and competencies in three areas of learning: content, scientific process, and application (learning how to learn).

Faculty collaboration is required to ensure that learning outcomes are mapped out for entire programs, departments, or even for a complete four-year curriculum, rather than only for individual courses. Frequent problems in mapping learning outcomes across courses are: (1) faculty's sense of proprietary ownership of individual courses; (2) disagreements about how to meet the needs of diverse audiences such as majors, nonmajors, and preservice teachers; and (3) differences of opinion regarding the need for prerequisites for courses.

Drawing on their own experience and expertise, workshop participants from different science disciplines were able to come to agreement on a set of learning outcomes and competencies for students in any introductory science course. The group concurred that desirable outcomes should include helping students to learn how to learn, to appreciate learning for its own sake, and to develop the skills necessary to understand both when they have learned and when they do not understand. Participants identified two challenges in achieving these desired outcomes. First, many students are resistant to learner-centered instruction, often because they have had little opportunity prior to college to develop independent learning skills or because they have been trained to focus on memorizable facts rather than on conceptual understanding. Second, students' preconceptions can be highly resistant to change, even with instruction that provides strong evidence that their interpretation is incorrect. As we will illustrate in the next chapter, carefully designed science education research[4] identifies specific student difficulties and develops instructional strategies that are effective in correcting such misconceptions.

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[4] To distinguish between disciplinary research conducted in the subject area of specific science fields and research conducted on teaching and learning of the discipline, the terms "science research" and "science education research" are used respectively. If implemented according to well-established principles, both kinds of research can be "scientific" (NRC, 2002c).

# 3

# Evaluating Effective Instruction

To develop a list of criteria and benchmarks for evaluating effective science, technology, engineering, and mathematics (STEM) instruction, educators must agree on the characteristics of such instruction. If the aim is not only to teach science content but also to foster inquisitiveness, cognitive skills of evidence-based reasoning, and an understanding and appreciation of the processes of scientific investigation, then—as noted in Chapter 2—courses that consist solely of traditional lectures and laboratory sessions may be inadequate. Moreover, if introductory science courses are expected to play even broader roles—such as increasing the likelihood that nonmajors and preservice teachers will choose to take additional science courses, and expanding the number of students who go into science and engineering careers—evaluation of introductory science instruction must be improved and appropriate criteria developed.

In this chapter, evidence is considered that defines the characteristics of effective instruction. In the workshop, participants were asked to enumerate features that could be included in a comprehensive evaluation instrument as indicators for rating exemplary STEM programs. While workshop breakout groups specified characteristics of programs of effective instruction, two presenters offered instructional techniques that exemplify many of these characteristics. Paula Heron, University of Washington, illustrated the tutorial program at her university designed to address students' preconceptions and details evidence that students gain improved conceptual understanding. Brian Reiser, Northwestern University, described a scaffolding tool and classroom environment that gradually builds students' skills for multidirectional instruction (i.e., teacher to student, student to teacher, student to student) and independent learning. Other workshop participants imparted additional instructional strategies that would achieve desired learning outcomes.

To begin to shape how criteria would be used to evaluate such instruction and programs, two presenters offered examples of assessment strategies and tools. Gloria Rogers, Rose-Hulman Institute of Technology, described the fundamentals of evaluation for any educational program. Anton Lawson, Arizona State University, illustrated an instructional assessment tool and the contexts in which it was used as an example of how to measure effectiveness of instruction. Expanded summaries of the presentations, the learning outcomes proposed by workshop participants, as well as additional ideas and cautions put forward by participants during plenary discussions are detailed within this chapter.

## CHARACTERIZING EFFECTIVE INSTRUCTION WITH RESEARCH EVIDENCE

Recent evidence suggests that, for many students, traditional didactic lectures that promote memorization of factual information may be unexpectedly ineffective for eliciting learning of more complex concepts when applied as the primary instructional method in science courses (Terenzini and Pascarella, 1994; Honan, 2002; Loverude, Kautz, and Heron, 2002). Although direct instruction is useful in some settings (e.g., Klahr, Chen, and Toth, 2001), and the lecture format can be improved by allowing learners to grapple with an issue on their own before they are provided with answers (Schwartz and Bransford, 1998) or by other modifications that add an element of interactivity (NRC, 2000; Laurillard, 2002), accumulating research indicates that the traditional approach with no additional cognitive assistance leads to memorization of facts rather than understanding of concepts for a majority of students (Wright et al., 1998; Loverude et al., 2002; see Appendix B, this volume). The evidence indicates, moreover, that most students who sit passively in lectures for an entire course are unlikely to appropriately link their prior conceptions to the new knowledge being presented. The conceptual misunderstandings they have when they enter a course are likely to persist if instruction does not address their difficulties specifically (King, 1994; Mestre, 1994; Loverude et al., 2002; Marchese, 2002). Even students who receive good grades and persist in science courses often gain little understanding of the basic science concepts (see Appendix B, this volume; Sundberg, 2002).

The broadened roles of introductory science courses, plus recent gains in understanding how people think and learn, have forced a reconsideration of what is meant by effective science teaching. Two recent NRC volumes mentioned earlier, *How People Learn: Brain, Mind, Experience, and School* (2000) and *Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics* (2003), describe numerous research findings that have powerful implications for how instruction might be organized and implemented to elicit learning. One of the hallmarks of the emerging science of learning is its recognition that students bring with them diverse learning styles and that they learn in different ways under different circumstances. This finding suggests that there is not likely to be one best mode of instruction for all purposes. Precollege educators recognize this need by utilizing a "learning cycle" (Stephans, Dyche, and Beiswanger, 1988) that engages students' intellectual curiosity before introducing formalisms. To be effective, undergraduate teaching faculty must also have at their command an aggregate of instructional strategies and be prepared to use combinations of inquiry-based, problem-solving, information-gathering, and didactic forms of instruction under appropriate classroom circumstances that promote conceptual understanding and students' ability to apply knowledge in new situations (Stephans et al., 1988).

When implemented properly, the evidence suggests that inquiry-based instruction and problem-solving strategies engage the learner in developing the mental models required for conceptual understanding (NRC, 2000, pp. 239–241). These strategies assist students in assimilating new information through interaction with their prior concepts and knowledge of the world outside the classroom. When combined appropriately with direct instruction and other teaching approaches, students are motivated to identify and gather relevant factual content and integrate that new knowledge with their preconceptions (Loverude et al., 2002; Marchese, 2002). With such instruction, these studies show that learners can be helped to absorb new facts and concepts, to devise and carry out scientific investigations that test their ideas, and to understand why such investigations are uniquely powerful as a way of learning.

## DEFINING CHARACTERISTICS OF EFFECTIVE INSTRUCTIONAL PROGRAMS

One of the goals of the workshop participants was to determine if it was possible to reach agreement on the characteristics of an effective instructional program. In the first breakout session, the disciplinary groups were assigned three tasks: (1) on the basis of the knowledge and expertise of the assembled group, develop a list of highly regarded courses/programs within the discipline; (2) consider the characteristics of each entry that justified its selection for the list; and (3) extract from those characteristics a list of criteria or indicators that would enable an observer to assess programs in that discipline.

## The Summaries of Breakout Groups

Priscilla Laws, Dickinson College, summarized the discussions of the physics working group. The group made a list of thirteen curricular materials and approaches in physics[1] that the members believed from personal experience had exemplary characteristics. They then set out to define explicitly the characteristics of these courses or course materials in physics that justified their designation as "exemplary." The identified characteristics are described below, following the summaries of the breakout groups, and reflect the importance of developing students' understanding of underlying concepts.

As noted above, many of these curricula utilize a process known as learning cycles (Kolb, 1984; Healey and Jenkins, 2000). A learning cycle is designed to engage students' curiosity about a phenomenon, to elicit their thoughts and preconceptions about the phenomenon, then to provide them with opportunities for direct observations and problem-solving experiences so they may judge the validity of their ideas, and finally to provide opportunities to resolve any discrepancies between their preconceptions and canonical concepts. The group pointed out that

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[1] The exemplary programs and approaches identified by the physics working group included context-rich cooperative problem solving (Heller, Keith, and Anderson, 1992; Heller and Hollabaugh, 1992), Explorations in Physics (http://physics.dickinson.edu/~EiP_homepage/html), Interactive Physics (http://www.interactivephysics.com), Just in Time Teaching (http://webphysics.iupui.edu/jitt/jitt.html), lecture demonstrations (Sokoloff and Thornton, 1997), Models in Physics Instruction (http://www.physics.umd.edu/perg/papers/redish/jena/jena.html), *Peer Instruction* (Mazur, 1997), *Physics by Inquiry* (McDermott, Shaffer, and Rosenquist, 1996), Powerful Ideas in Physical Science (http://www.psrc-online.org/classrooms/papers/layman.html), Real Time Physics (http://physics.dickinson.edu/~wp_web/Introduction/FAQ/Real_Time_Physics), Studio Physics (http://www.rpi.edu/dept/phys/education.html), *Tutorials in Introductory Physics* (McDermott, Shaffer, and the Physics Education Group, 2002), and *Workshop Physics Activity Guide* (Laws, 1997).

many students of different majors and diverse needs are required to take physics. The physics community generally requires students to learn what the experts feel is important for them to know without seeking input from students. All too often, this is achieved by simply telling students what to memorize through a series of traditional didactic lectures. In contrast, Laws noted "One of the things most of the reform curricula have in common is…a great emphasis on [the need for] students understanding the underlying…concepts [while recognizing that] one of the real weaknesses of traditional [instruction] is that students …memorize how to solve categories of problems…without understanding the fundamental underlying concepts."

Marshall Sundberg, Emporia State College, summarized the life sciences group's discussions of a range of examples, such as those listed in the NRC report *BIO2010* (2002a) in which instructors provide class-based investigative opportunities, both for students majoring in the sciences and for nonmajors. The characteristics representative of a number of successful programs are described below following the summaries. In all cases, an important feature was that the instructor sought to build learning communities that engaged students and encouraged further study.

David Gosser, City College of New York, and Ishrat Khan, Clark Atlanta University, summarized the discussions of the chemistry group. This was a small group, with most members currently involved in the same projects—New Traditions (http://newtraditions.chem.wisc.edu) and Peer-Led Team Learning (PLTL) (http://www.pltl.org). The noteworthy characteristics of these programs are that they engage faculty in teaching, require incremental changes, and take into account forces that drive institutions. The group identified additional characteristics that make these programs exemplary and discussed other methods to engage faculty, outside of those immediately invested in educational reform, to adopt effective instructional strategies. These characteristics and methods are described below following the summaries.

Khan cited New Traditions and PLTL as efforts that are designed to be readily adaptable to different settings but which also allow faculty ownership of material and assessment. Gosser added that with PLTL, faculty are asked to evaluate students and report findings to the parent program; he believed this data collection convinces faculty that the model is working and provides them with resources to support the program at their institutions. He also noted that students are involved in efforts to disseminate PLTL. "They…actually conduct workshops and show faculty how poised and how capable they can be. This is more of a selling point than if I talk about it for an hour." In response to questions by Richard McCray, University of Colorado, Gosser and Khan confirmed that the PLTL program could be adapted for other disciplines. Susan Singer, Carleton College, added that the program has already been modified and is being used in history and introductory biology.

Bonnie Brunkhorst, California State University, San Bernardino, summarized the discussions of the geosciences group that included representatives from the fields of geosciences, space science, and astronomy. The group chose to look at NSF-funded projects and examined the criteria that had been developed out of those projects. McCray added that since the group had a hybrid representation, their discussions were not discipline specific.

## The Characteristics of Effective Programs

The characteristics of exemplary programs identified by the geosciences group and other breakout groups are described below. The characteristics were very similar across the disciplinary groups. Recognized exemplary instructional programs can be characterized as follows. They:

- **Provide experiences for students to develop functional understanding.** These programs place emphasis on students' understanding of science concepts and ability to apply these concepts to new situations. Less emphasis is placed on end-of-the-chapter problems and exams as the bottom line in grading, to minimize students memorizing and pattern matching without developing functional understandings. The programs often outline the concepts they expect students to learn as explicit learning outcomes (see the partial list of concepts for biology education in Table 2-1 for an example). Opportunities for undergraduate research were identified as appropriate experiences to develop an understanding of the scientific process.
- **Have strategies for iterative evaluation.** These strategies should include self-assessment by faculty of instruction and program effectiveness, mechanisms for identifying instructor expertise both conceptually and pedagogically, assessment of student learning, and procedures for learning from failure through formative evaluation. Exemplary programs often take risks, learn from failure, reevaluate, and try again. Summative evaluation is needed to demonstrate effectiveness to developers or institutions.
- **Invest in training and mentoring of instructors, both**

**faculty and teaching assistants.** Training should assess in a nonthreatening manner the instructors' competencies and comfort levels for the program. Training should encourage instructors to take ownership of the program and its materials and to adapt it as necessary to suit their own contexts.

- **Include efforts to collect and disseminate information about the program, applying accepted principles of research on teaching and learning**.
- **Make interdisciplinary connections.** Instructors should make students aware that methods or concepts from other sciences are often used in the context of one discipline.
- **Foster independent learning skills.** These programs strive for the outcomes regarding learning skills (i.e., "learning to learn") defined in Chapter 2.
- **Promote students' ability to work cooperatively and to communicate orally and in writing.**
- **Address materials' relevance to students.** The working group agreed that material should be relevant to students' lives, but they pointed out that sometimes the topics that have the biggest impact are not perceived as relevant initially but become surprisingly significant.
- **Become institutionalized and self-sustaining.** Strategies exist for departments to take group ownership of effective programs. Institutionalizing effective programs is critical to sustain the programs in the event that the individuals driving the programs retire or otherwise leave.

## ACHIEVING DESIRED OUTCOMES WITH EFFECTIVE INSTRUCTIONAL TECHNIQUES

As noted earlier, there is accumulating evidence that new knowledge is shaped by interaction with existing knowledge (NRC, 2000). Instructors need to pay attention to students' beliefs, incomplete understandings, and the naïve versions of concepts they bring to a given subject. An important element of effective instruction involves building on these preconceptions and prior beliefs in ways that help each student achieve a more mature understanding. If students' initial ideas and beliefs are ignored, the understandings that they develop can fall far short of the goals of the instructor (Minstrell, 1989; Mestre, 1994; NRC, 2003). Striking evidence for this comes from a study in which undergraduates in a leading university who took a traditional geometry course that ignored their entering misconceptions represented and visualized three-dimensional forms more poorly than did a comparison group of elementary children whose prior ideas about space were engaged (Lehrer and Chazan, 1998). This discussion of the resistance of students' preconceptions to change was the setting for Paula Heron's contribution.

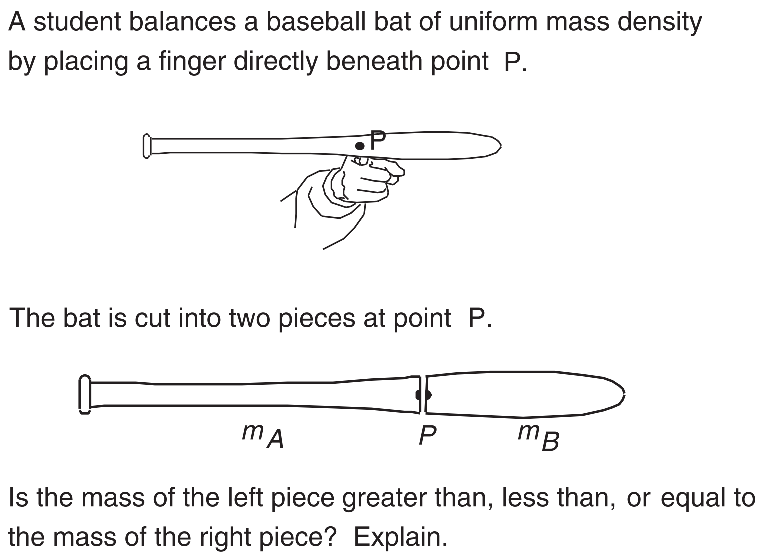
### Instruction Designed to Help Students Overcome Conceptual Difficulties

*Paula Heron, University of Washington*

In her presentation entitled *Research as a Guide to Improving Student Learning in Undergraduate Physics*, Heron illustrated how misinterpretations or problems that students have with specific ideas can persist and adversely affect desired learning outcomes. She described how the university's Physics Education Group (PEG) conducts research to develop effective instructional strategies to address the difficulties students commonly have with specific physics topics. Heron stressed the importance of education research that is conducted within the discipline. "What physics education research constitutes is an approach to improving instruction that is objective [and] efficient and allows for cumulative progress to be made in the teaching of the discipline." She illustrated this perspective with a specific example of research that focused on student understanding of the concept of center of mass (Gomez, 2001).

The "baseball bat problem" (see Figure 3-1) tests whether students recognize that both the amount of mass and its distribution determine the location of the center of mass, or the balancing point. The problem was administered to students at different stages of instruction in different courses. Responses from students in the introductory calculus-based physics course at the University of Washington (UW) were compared before and after traditional instruction in the course and after additional *Tutorials* (McDermott, Shaffer, and the Physics Education Group, 2002). Tutorials at UW meet once a week, while lectures are held three times a week. (Students participate in a weekly lab as well.) In the tutorials, students work with materials and complete worksheets tailored specifically to guide them through the development and application of important concepts in the course, and to address specific difficulties that have been uncovered through research.

Responses to the bat problem were also gathered from students in an introductory calculus-based physics course at Purdue University, where the tutorials developed at UW have been incorporated, and from students in an introductory engineering statics course at UW. These students, who are required to take an introductory calculus-based physics course prior to the statics



A student balances a baseball bat of uniform mass density by placing a finger directly beneath point P.

The bat is cut into two pieces at point P.

Is the mass of the left piece greater than, less than, or equal to the mass of the right piece? Explain.

FIGURE 3-1 The baseball bat problem.
SOURCE: Gomez (2001). Reprinted with permission.

course, revisit material on the center of mass in the statics course. Responses were also obtained from prospective and practicing K–5 teachers in special physics courses at UW that are designed to prepare them to teach physics and physical science as a process of inquiry. Table 3-1 presents the results from the bat problem: the percentages of students answering the question correctly sorted by type of instruction received.

The results from the bat problem were consistent with those obtained in other studies by PEG related to student conceptual difficulties with the wave properties of light (Ambrose, Heron, Vokose, and McDermott, 1999) and compression of ideal gases (Loverude et al., 2002). Cumulatively, the group's research findings indicate that on certain types of qualitative questions, student performance remains essentially unchanged before and after instruction in either calculus- or algebra-based courses, with or without standard laboratory, with or without demonstrations, in large and small classes, and regardless of perceived effectiveness of the lecturer (see Appendix B, this volume).

Heron summarized the group's interpretation of their data with a question: "Is…good quality standard instruction, through a lecture, textbook, and laboratory, sufficient to develop a

TABLE 3-1 Student Response to Baseball Bat Problem (Percentages by Course)

| Course and Relative Time of Test | N | Percentage Responding $m_A < m_B$ (correct) | Percentage Responding $m_A = m_B$ |
|---|---|---|---|
| Introductory mechanics, University of Washington, before instruction | 152 | 5 | 90 |
| Introductory mechanics, University of Washington, after instruction | 455 | 15 | 80 |
| Engineering statics, University of Washington, after all instruction | 71 | 15 | 85 |
| Introductory mechanics, University of Washington, after traditional instruction plus tutorial | 255 | 55 | 40 |
| Introductory mechanics, Purdue University, after traditional instruction plus tutorial | 1,160 | 50 | 45 |
| Graduate TAs, University of Washington, after traditional instruction (presumed) | 30 | 70 | 30 |
| Physics by Inquiry course for preparing K–5 teachers, University of Washington, after instruction | 30 | 100 | 0 |

SOURCE: Gomez (2001). Reprinted with permission.

functional understanding of an important concept or principle? By functional understanding, what we mean is the ability to apply the concept or principle to a situation that has not previously been memorized." Her answer, based on PEG research and a growing body of other supporting literature was: "Teaching by telling is an ineffective mode of instruction for most students…. Students must be intellectually active to develop a functional understanding…. Sitting and listening to lectures…, reading the textbook, solving the traditional end of chapter problems does not lead to this type of intellectual engagement."

Heron pointed out that even instruction considered to be "pedagogically correct," such as small group work, hands-on activities, and demonstrations, may not address persistent conceptual and reasoning difficulties. When students in the engineering statics course participated in small group exercises devoted to centroids and center of mass, there was no evidence of improved performance on the bat problem. The percentage of students who claimed that the halves of the bat on each side of the balancing point must have equal mass was the same as in the prerequisite introductory physics course. In response to a question by Lawson about whether students would be affected by faculty demonstrating the different masses of bat "halves" by weighing the pieces obtained from cutting the bat at the balance point, Heron described an instructor's experience in conducting such a demonstration. When confronted with the evidence, students assumed that the demonstration had not worked as planned. "We know what we were supposed to see," they said to the instructor. Heron indicated that in laboratory situations students would often ask for better equipment if the results fail to match their (erroneous) expectations.

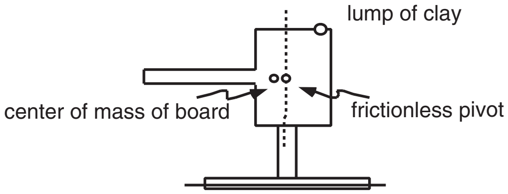
During her presentation, Heron made the point that effective instruction could best be designed through research to identify and detail specific student difficulties and assess instructional strategies meant to address those difficulties. By examining student responses to the bat problem, as well as to several other written problems, and probing student ideas through in-depth interviews, Heron and her colleagues identified several specific student difficulties with the concept of static equilibrium. Of primary concern was the failure of students to consider both the mass and its distribution relative to the balance point.

Heron explained how tutorials incorporated into introductory physics courses at the University of Washington are designed to address students' conceptual and reasoning difficulties

Hang board from a hole to the right of the center of mass.

Use clay to balance the board.

Predict how the total mass to the right of the pivot compares to the total mass to the left.



a. Move the clay toward the pivot.

Does the board remain balanced?
Does the total mass to either side of the pivot change?

b. Balance board again using larger piece of clay.

Does the total mass to either side of the pivot change?

FIGURE 3-2 Excerpt from tutorial "Equilibrium of Rigid Bodies."
SOURCE: McDermott, Shaffer, and the Physics Education Group (2002, p. 65). Reprinted with permission of Prentice-Hall.

and to provide a mechanism for securing intellectual engagement despite large classes. Heron described an excerpt from the tutorial entitled "Equilibrium of Rigid Bodies," in which students explore the effects of repositioning a piece of clay on an odd-shaped board balanced on a nail (see Figure 3-2). Benefiting from the research on student difficulties, this tutorial is designed to lead students to recognize that both mass and its distribution relative to the pivot point influence balancing. Correct responses by students on the bat problem increased threefold after this tutorial was incorporated into the UW introductory physics course. A comparable improvement was observed at Purdue University, where the same tutorial was introduced. (Results at Purdue after traditional instruction alone are very similar to those obtained at UW.)

To emphasize further the importance of instruction that specifically addresses persistent difficulties, Heron described another effort of PEG: a self-contained laboratory-based curriculum to prepare K–12 teachers to teach science as a process of inquiry. *Physics by Inquiry* is a set of instructional modules (McDermott, Shaffer, and Rosenquist, 1996) that are designed to achieve four primary objectives: (1) develop conceptual understanding and reasoning ability in the context of a coherent subject matter; (2) develop specific scientific reasoning skills (control of variables, proportional reasoning, etc.); (3) develop skills in using and interpreting scientific representations (graphs, diagrams, equations, etc.); and (4) provide direct experience with the process of science. Upon completion of the unit that deals with balancing, all of the participating K–5 teachers answered the bat problem correctly, whereas none had done so prior to the unit.

### Tutorials That Address Students' Difficulties

The tutorial system described in Heron's presentation has been shown to be effective in improving student learning. (For a description of the tutorials and their implementation at UW, see, for example, McDermott, 2001.) Weekly pretests are given in the tutorials to elicit student difficulties about the topic. The pretests are administered before the tutorial but usually after lecture instruction on the topic. In the tutorials, students work in small groups (3–4) using carefully structured worksheets; instructors are prepared to teach by questioning; and questions related to the tutorials are included on every course exam. Heron emphasized that interactive lectures, small group work, and hands-on activities are appropriate techniques to promote student learning but are not sufficient in and of themselves to engage students at a sufficiently deep intellectual level. Unless serious conceptual difficulties are addressed explicitly, they are likely to persist and preclude meaningful learning not only of the topic under consideration, but of others for which it is a prerequisite.

Both Heron and the subsequent presenter, Brian Reiser, detailed instructional strategies that would address the challenges in achieving desired learning outcomes. Heron's presentation highlighted the importance of science education research[2] to identify persistent difficulties that hinder students' conceptual understanding. Reiser described a "scaffolded" learning environment that gradually shifted students from learning in lecture-based classrooms to learning in interactive, multiresource classrooms. During the plenary discussion that followed Heron's and Reiser's presentations, other participants identified additional effective instructional strategies.

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[2] See distinction between science research and science education research made in footnote #4, Chapter 2.

## Scaffolding Tools

*Brian Reiser, Northwestern University*

In his presentation *Supporting Investigation and Argumentation in Science Classrooms*, Reiser described a learning environment, known as Biology Guided Inquiry Learning Environments (BGuILE) (http://www.letus.org/bguile/overview.html), supported by the Center for Learning Technologies in Urban Schools (LeTUS) (http://www.letus.org). Scaffolded experiences are intended to work like an apprenticeship, whereby an expert (the instructor, teaching assistant, or a peer learning coach) models a problem-solving activity, then provides the learner with advice and examples, guides the learner in practice, and finally tapers off support and guidance until the student can do it alone (Collins, 1990). Scaffolding can be provided by a computer-based resource (White and Frederickson, 2000), as well as by an instructor, as in the case of BGuILE.

Building scaffolding into a software tool in addition to in a person has motivated Reiser's work for the last ten years. The teacher and software both have essential roles in the curriculum, which Reiser described and demonstrated through video clips and recorded classroom conversations. The teacher's role in these classrooms is to help students care about the material, engage students in the problem under consideration, provide assistance with tools, and structure classroom discourse around appropriate ideas. The computer tools of the BGuILE program encourage and teach students to manipulate only one variable at a time, to write better hypotheses, to look for disconfirming evidence, and to write down their observations, findings, interpretations, and questions continuously. In this light, Reiser defined the scaffold as "a teacher or more knowledgeable peer [who] assists a learner, so he or she can solve problems that would otherwise be out of reach."

In BGuILE, four computer-based scenarios and associated classroom activities are designed to help students learn biology by exploring significant research problems. The scenarios selected are rich in data so that students do not all arrive at the same conclusion but rather must defend their answers. Reiser illustrated the teaching strategies through one of the scenarios, a problem-based unit on ecology and evolution called *The Galápagos Finches*. Once the teacher has "sold" students on the significance of the *Galápagos Finches* problem the students will learn skills for graph interpretations and scientific argumentation, as well as something about natural selection, intraspecies interactions, and balance in ecosystems, through the scaffolding software tools.

Though much of Reiser's work is at the K–12 level, he identified his purpose for presenting at this workshop as exploring whether his work to help middle and high school students go beyond the formalisms (memorized equations and terms) and develop functional understandings can be replicated at the undergraduate level. Reiser provided an example of a group working with the scaffolding tool; the participants believed they had reached consensus, but when they were forced to write in the tool they discovered disagreements and the need to further clarify definitions.

To employ the strategies essential for effective inquiry teaching, Reiser explained, instructors needed to change the climate of the classrooms. He pointed out examples of such climate changes in his video presentations. The teacher would often engage students in questions about the problem and would frequently profess that the answers are not known. At the start of the school year, the students did not believe her and felt she was holding back answers. Through continued discussions, they began to accept her acknowledgement and to articulate explanations on their own or through discussions with their peers.

Reiser highlighted a student in a full class discussion who asked a question of his classmates instead of the teacher. Students need to interact with each other and the teacher in new ways. They have to be willing to explain their thinking, to ask questions of each other, and to offer advice to other students. Teachers have to continually engage students in conversations and questions about the problem under consideration. Both the teacher and the software tool aim to uncover students' confusions and then guide the students into productive discussions about these confusions.

### Small Group and Pair Cooperative Learning

Extending the idea that students should be more engaged in conversations and questions with instructors and peers, several workshop participants pointed to the benefits of student-to-student interactions. For example, Michael Zeilik, University of New Mexico, asserted that students' conceptions can be changed in properly managed cooperative teams and that small group or pair cooperative learning can be facilitated even in large lecture situations (Mazur, 1997; Schwartz and Bransford, 1998). Priscilla Laws, alluding to Heron's message about targeting persistent difficulties, added that students must engage with the right issues if cooperative teams are to be successful. She pointed out that lecture demonstrations can be effective, referring to an article by Sokoloff and Thornton

(1997), if students are engaged in discussions about what they saw and what they conclude.

Confirming that cooperative groups can be effective, Elaine Seymour, University of Colorado, added that students often complain about this approach, but if the instructor continues to form and work with such groups the students become more comfortable with collaborative learning. She also reported that men get the most out of structured groups because such work tends to be novel to them; women, in general, need little prompting to work in groups (e.g., Stabiner, 2003). Richard McCray added that in situations where students are forced to explain their answers and reasoning, they are able to identify what it is that they don't understand.

### Case Studies

In addition to instructional methods that encourage collaboration, another strategy that many participants thought to be effective was the use of case studies. Katayoun Chamany, Eugene Lang College, reminded the group that subject matter could be made relevant and useful to diverse populations of students by teaching through case study modules. In support of Chamany's point about incorporating case studies into the curriculum, Clyde Herreid, State University of New York at Buffalo, explained that, like other inquiry-based approaches to teaching and learning, case studies promote interaction and provide relevance for the students (Herreid, 1999; Honan and Rule, 2002).

### Problem-Based Learning

Both Herreid and Zeilik promoted PBL as the "greatest method of all." Herreid pointed out that the PBL method, as described in *The Power of Problem-Based Learning* (Duch, Gron, and Allen, 2001), has thrived successfully at many medical schools for over thirty years. However, it has also failed at a few medical schools because of lack of administrative support.

### Instructors' Roles and Physical Environment

In his presentation later in the workshop, Jack Wilson, UMassOnline, identified some teaching methods that were relevant to include with this section. In his talk, he listed some of the strategies that made Studio Physics successful at Rensselaer Polytechnic Institute. The major instructional innovation was in the interaction between the instructors (faculty and teaching assistants) and the students. Instructors in the Studio define their role as guides, leading students to information and helping them with difficult concepts, while students are encouraged to take responsibility for their own learning.

Anton Lawson added that instructors should be aware of the reasoning skills and abilities students have when they enter their classrooms and the need to focus on developing those to a higher level throughout the course. Although assessing generalized cognitive skills is more difficult than measuring discipline-specific knowledge, there is a substantial literature on how to do it (Shavelson and Huang, 2003).

In Studio Physics, teaching assistants work collaboratively with faculty; one faculty member, one graduate TA, and one undergraduate TA interact with students together in each studio section. The team approach reduced the error rate on transmitted information, since if one of the three misunderstood the problem the others could make corrections. The physical setting for the course was completely reconstructed from two theatre-style lecture sessions serving 500 students each to 12–15 studios or labs where 50–60 students worked in small collaborative groups. Instruction was extended through the mobile computing initiative, requiring a laptop computer for each student. Laptop purchases were built into the financial aid structure such that a student receiving 100 percent financial aid was given a laptop. Most of the didactic material for the course was made available online.

Recognizing the importance of all the suggested instructional methods—including Studio Physics, problem-based learning, case studies, in-class conversations and small group work, scaffolding tools, and the tutorials at UW—Ronald Henry, Georgia State University, remarked that faculty should model in their teaching the ways in which their own students should teach if those students go on to become graduate teaching assistants, K–12 teachers, or science faculty.

## ASSESSING INSTRUCTIONAL IMPACT ON LEARNING

During their deliberations, each of the workshop breakout groups developed lists of student learning outcomes appropriate for introductory science courses (see Chapter 2). But according to Herb Levitan, National Science Foundation, many faculty members do not know how to evaluate either student learning achievements or their own instructional efforts. Moreover, added Lawson, although many current evaluation practices measure performance on tests or other tasks, they fail to indicate the degree of learning. Learning, in this context, is interpreted as conceptual understanding measured by the ability of a student to apply knowledge and skills in new situations. This discussion served as background for the two speakers at the workshop who devoted their presentations to assessment practices and tools, one to provide general background information, the other offering an example of an instrument for evaluating an instructor's performance in the college classroom.

## Fundamentals of Evaluation

*Gloria Rogers, Rose-Hulman Institute of Technology*

In her presentation *Evaluating student outcomes: E=MC²*, Rogers emphasized the importance of establishing a complete institutional assessment process, covering classroom assessment, program assessment, and "mapping strategies" (i.e., methods for using assessment data to chart instructional improvements across a program). Recognizing the wide range of expertise of the workshop participants, she aimed to include information designed to link classroom and program assessments.

### *The Purpose of Assessment*

The most difficult part of assessment for faculty, Rogers noted, is to define explicitly what is meant by educational outcomes, and to articulate outcomes in terms of measurable criteria.

### *Definition of Terms*

Since many of the terms commonly used in the field of assessment are defined only vaguely, Rogers stressed the importance of agreeing on definitions at the start of an evaluation process to avoid future disagreements. Rogers distinguished "assessment," the collection and analysis of evidence, from "evaluation," which she defined as interpretation of evidence. She emphasized that these were separate activities. She also defined inputs, processes, outputs, and outcomes. See Table 3-2 for examples of each of these terms. Each term includes student, faculty, and campus components.

Inputs were defined as what the constituents bring into the system. Processes include the programs, services, loads, policies, and procedures that are established to take advantage of what is known about the inputs. Outputs are easily measured indicators and statistics. Outcomes refer to the effects, which are particularly important in terms of accreditation.

### *Goals of Assessment*

Rogers focused next on the importance of determining what is being assessed. Is the target of the assessment individuals or groups? Will the assessment be used to evaluate achievement, placement, gatekeeping, program enhancement, or program accountability? She indicated that the assessment strategy would be dependent on assessment goals.

TABLE 3-2 Examples for Assessment Terms

| Inputs | Processes | Outputs | Outcomes |
|---|---|---|---|
| Student credentials: Test scores | Programs and services offered, populations served | Student grades, graduation rates, employment statistics | What have students learned; what skills have they gained; what attitudes have they developed? |
| Faculty credentials | Faculty teaching loads/ class size | Faculty publication numbers | Faculty publication citations data, faculty development |
| Campus resources | Policies, procedures, governance | Statistics on resource availability, participation rates | Student learning and growth |

SOURCE: Adapted by Rogers (2002b) from work cited in Middaugh, Trusheim, and Bauer (1994, p. 4).

With input from workshop participants, Rogers identified stakeholders in the educational process as students, their parents, other departments, employers, scholarship agencies, and graduate programs. She noted that the constituents have different expectations and the makeup of constituents can vary widely from institution to institution. She pointed out that educational objectives should be tied to the institutional mission and should be reevaluated every several years. To accomplish the educational objectives, students must achieve learning outcomes, which Rogers defined as what students should know and be able to do by the end of a course or program. Instructors, she suggested, should build educational practices and strategies around desired learning outcomes, incorporating measurable performance criteria into the curriculum to determine whether those outcomes are achieved.

Each aspect (objectives, criteria, practices/strategies, assessment, outcomes, evaluation, and constituent responses) is part of an interconnected system of feedback for continuous improvement of the course or program. Rogers stressed the importance of defining and reevaluating: "If objectives and outcomes are difficult to define, they will be difficult to measure." Ramon Lopez, University of Texas at El Paso, asked about the effectiveness of the Accreditation Board for Engineering and Technology criteria (2002). These standards, which emphasize outcomes and understanding for undergraduate engineering students, were intended to drive real change in engineering programs. Rogers responded that while the ABET 2002 criteria themselves are excellent, many schools have responded with “surface” changes and most engineering programs have not taken a hard look at defining outcomes, or teaching in relation to these outcomes. Most programs depend on exit surveys that ask graduating seniors and employers if certain knowledge and skills have been achieved.

Rogers pointed out, however, that even these surface changes could have some significance. Programs are beginning to recognize the importance of defining learning outcomes and to map and identify gaps in their curriculum. Alan Kay, Viewpoints Research Institute, Inc., drew attention to the bigger picture of outcomes, or enlightenments, such as those that enable individuals to invent entirely new technologies that could not be easily measured but would play powerful roles in future innovations. Rogers acknowledged the significance of his point, but reiterated that defining explicit learning outcomes is necessary, because instructors and institutions are accountable for assessing student learning and “we can’t assess it if we don’t know what to expect.”

### *Classroom versus Program Assessment*

Rogers outlined the similarities and differences between classroom and program assessment. Both can be formative and/or summative; both measure knowledge, skills, behaviors, attitudes, and values; and both focus on individual students or groups of students. The differences entail the degree of complexity, time span, cost, level of specificity of the measure, degree of accountability for the assessment process, and level of faculty commitment. Rogers identified constraints on assessment and practices that should be taken into consideration: time, facilities, subject matter relevance, and student knowledge factors such as differences in preexisting knowledge, out-of-class experiences, and selected sequence of courses.

She continued by describing what she referred to as “mapping strategies”: procedures for identifying where in the curriculum students have the opportunities to learn, apply, and demonstrate the knowledge and skills proposed in the learning outcomes. The process of mapping informs the instructor or administration about existing opportunities as well as gaps in the course or program. Rogers shared her vision of a syllabus for students that detailed their opportunities and responsibilities to gain specific knowledge and skills. Faculty members at her institution receive a curriculum map every quarter and are asked to indicate learning opportunities in their courses as they relate to the learning outcomes projected by the department or institution.

Rogers listed common assessment methods and made available a booklet she authored, *Evaluating Student Learning: E=MC² Assessment Methods* (2002), which describes available tools in detail: standardized exams, local developed exams, oral exams, performance appraisal, simulations, written surveys and questionnaires, exit and other surveys, focus groups, external examiners, behavioral observations, archival records, and portfolios. She concluded with some words of motivation for the participants: start early with assessment plans, prioritize, pick appropriate battles, seek out resources and reference materials, recognize that any one assessment plan does not fit every situation or institution, and adopt various strategies from different sources to meet individual needs.

Anticipating the discussion in Chapter 4, Rogers noted that if an institution wishes to encourage and reward excellence in instruction, it must have an established set of goals that any course is expected to achieve and a reliable means of distinguishing between instructional strategies that are more effective and those that are less so in reaching those goals. Yet, despite the importance of evaluating teaching, most colleges and universities continue to struggle with the question of how to do it (Seldin, 1999). A common method of evaluating faculty is through student ratings. However, more reliable and productive assessments rely on multiple sources of evidence. Faculty may also be evaluated by examination of teaching portfolios that describe course organization and teaching materials, determination of level of student learning, evaluation by peers and administrators, and classroom observations by an instructional consultant (Seldin, 1999; Fink, 2002). Numerous teaching observation and evaluation instruments are described in the literature (reviewed in Wilkerson and Lewis, 2002; NRC, 2003).

### An Instructional Assessment Tool

*Anton Lawson, Arizona State University*

In his presentation *Tools for Assessing Quality USTEM Instruction: Reformed Teaching Observation Protocol (RTOP)*, Lawson described the context for the development of the RTOP instructional assessment tool, and also highlighted many of the significant findings from the application of RTOP by faculty of the Arizona Collaborative for Excellence in the Preparation of Teachers (ACEPT).

(See details in Lawson's paper in Appendix A, this volume.)

Following best practices in faculty development (Wright, 2002), ACEPT introduced summer training institutes in which college faculty could experience teaching methods based on the principles of effective teaching introduced by the American Association for the Advancement of Science (AAAS) in *Science for All Americans* (1990). These principles emphasize that teaching should be consistent with the nature of scientific inquiry and recommend many of the teaching approaches discussed earlier in this workshop by Heron, Reiser, and others (see Lawson's paper, Appendix A). Lawson's group then employed the RTOP instrument to evaluate whether the institutes had an effect on faculty's use of ACEPT teaching methods in their courses and whether these teaching methods in turn had an effect on student achievement. (Details are available at http://purcell.phy.nau.edu/AZTEC/RTOP/RTOP_full/index.htm, and in Lawson's paper in Appendix A.)

The 25-item RTOP observation instrument is organized into the following evaluation categories: lesson design and implementation, propositional and pedagogical content knowledge, classroom culture (interstudent and teacher/student interactions), and problem-solving orientation (Box A-2, Appendix A). On a Likert scale, an observer assesses a lesson on the basis of items such as: "3) In this lesson, student exploration preceded formal presentation"; "5) The focus and direction of the lesson was often determined by ideas originating with students"; "6) The lesson involved fundamental concepts of the subject"; "8) The instructor had a solid grasp of the subject matter content inherent in the lesson."; "11) Students used a variety of means (models, drawings, graphs, concrete materials, manipulatives, etc.) to represent phenomena"; "12) Students made predictions, estimations and/or hypotheses and derived means for testing them."; and "17) The instructors questions triggered divergent modes of thinking."

In an ongoing investigation of the ACEPT program, instructors were evaluated in five courses. To make meaningful comparisons, several instructors in each course were rated with the instrument. Various instructors who exhibited considerable variation in the extent to which they had embraced the reformed methods during the summer institute were selected for rating, as well as instructors who did not participate in the institute. The examined courses included an introductory physics and mathematics course (each designed especially for preservice elementary school teachers), a large introductory biology course, an introductory physics course for physics majors, and a biology course for preservice teachers taken near completion of their undergraduate biology majors. For each course, data included instructors' RTOP scores and students' scores and/or normalized gains on tests appropriate to each course.

Lawson outlined the significant findings from the ACEPT investigation. The reliability of RTOP was demonstrated to be quite high. Trained independent observers were found to rate individual instructors with similar scores. The important result of the investigation was that mean instructor RTOP scores correlated strongly ($r = 0.88–0.97$, $p < 0.05$, range of the five courses) with student achievement gains, supporting the hypothesis that ACEPT teaching methods promote higher student achievement. Additional evidence for this conclusion was the finding of improved student content knowledge and reasoning skills, as measured by an independent reasoning skills assessment. Furthermore, a significant correlation ($r = 0.70$, $p < 0.05$) was noted between the RTOP scores of the TAs responsible for the introductory biology course labs and students' reasoning gains as measured in those labs. In follow-up observations, the RTOP scores of in-service teachers who had received instruction at Arizona State from instructors who had participated in ACEPT courses were significantly higher than those who had not.

In a continuing investigation, Lawson reported that ACEPT is building evidence for extended positive effects of ACEPT instruction for preservice teachers on the achievement of high school students that they teach. Lawson concluded by pointing out that those RTOP scores, which indicate the degree to which ACEPT instructional methods are implemented, are strongly correlated with improvements in student achievement not only in terms of conceptual understanding but also in reasoning skills. The critical aspect of these instructional methods, according to Lawson, is that they include a broad array of research-based teaching strategies. "Our project was based…on the teaching principles that are found in the AAAS document called *Science for all Americans*, which basically states that teaching should be consistent with the nature of scientific inquiry. That means [one should] start with questions about nature. Engage students actively. Concentrate on the collection and use of evidence. Provide historical perspective. Insist on clear expression. Use a cooperative team approach and do not separate knowing from finding out and the memorization of textbook vocabulary."

In response to participants' concerns about the accuracy of a one-time "snapshot" evaluation of a faculty member, Lawson clarified that observations for these evaluations were conducted on three separate occasions for each instructor at a time when the instructors were introducing new topics in the classrooms. He concurred that an instructor's RTOP score could increase if observed over extended periods or in different circumstances, such as laboratory sessions. Richard McCray added that instructors must plan long-term methods to encourage students to become reflective about their learning; this does not occur in just one day. Lawson responded that the summer institutes did encourage developing such procedures and that their single classroom observations are assumed to be appropriate snapshots of the results.

## SUMMARY

The major points from the presentations and discussions concerning the characteristics of effective instruction and how such instruction may be assessed are summarized below.

Accumulating research shows that the traditional didactic lecture format can support memorization of factual information but may be less effective than other instructional strategies in promoting understanding of complex concepts or the ability to apply such concepts in new situations. Instructional programs known to the workshop participants to be effective in eliciting such learning start by defining important, measurable learning outcomes for students; recognize that students have diverse learning styles; provide varied experiences for students to develop functional understanding of a subject; promote students' ability to work cooperatively and to communicate orally and in writing; invest in training and mentoring of instructors; and promote research on teaching and learning. Classroom observation assessment instruments exist for evaluating an instructor's degree of success in achieving these goals.

An important element of effective instruction involves engaging students' preconceptions and prior beliefs in ways that help them achieve a more mature understanding. Effective instructional strategies for correcting misconceptions and producing conceptual understanding for most students require situations that demand active intellectual engagement, such as tutorials, small group learning, hands-on activities, case studies, and problem-solving exercises with appropriate scaffolding. Scaffolding (i.e., support and guidance in learning specific concepts or tasks) can be provided by an expert (instructor, teaching assistant, or peer learning coach) or by a computer program. When instructors employ effective instructional strategies of the types described, they model in their teaching the ways in which their own students should teach if those students go on to become graduate teaching assistants, K–12 teachers, or science faculty.

# 4

# Promoting Effective Instruction at Departmental and Institutional Levels

This chapter explores how effective instruction, as defined in Chapter 3, can be promoted within a university culture that is otherwise dedicated primarily to research and the advancement of science. It examines how the personality traits of individual faculty and the characteristics of organization, governance, and incentive structures of departments and institutions are related to teaching and instructional programs. It also considers qualities that serve as barriers to implementation of effective instruction. Six presenters at the workshop discussed these characteristics and qualities and offered strategies to promote more effective instruction. Expanded summaries of their presentations as well as additional ideas and cautions put forward by participants during plenary discussions are detailed within this chapter.

## UPGRADING THE CURRENT CULTURE

The current culture of science, technology, engineering, and mathematics (STEM) departments in most research-intensive (Research I and Research II) universities embodies the principles of the scientific disciplines represented. This is a culture that values the activities that lead to cutting-edge research: intense concentration on laboratory or field investigations, obtaining the grants needed to support that research, and training graduate students and postdoctoral fellows to extend it. As noted by Merton (1957), “On every side the scientist is reminded that it is his role to advance knowledge…. Recognition and esteem accrue to those…who have made genuinely original contributions to the common stock of knowledge" (p. 642). As documented in a recent NRC report, the culture that rewards research productivity more than teaching effectiveness has changed little on many campuses in the past half century (2003).

Little wonder then that those educational reformers who advocate that faculty enlarge their priorities to include major improvements in undergraduate teaching have met resistance. At present, faculty members are likely to face significant disincentives to learn new teaching approaches and reformulate an introductory course: it requires a large investment of time, it is a distraction from the focus on research, and their investment may not be rewarded. In the NRC report *Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology* (1999), the Committee on Undergraduate Science Education suggests a four-point effort to reformulate faculty incentives. The recommended reformulation would encourage faculty to learn new effective approaches to teaching such as those outlined in Chapter 3 of the present volume and to develop new courses based on such knowledge. That report includes the following recommendations: (1) Administrators should provide faculty with the resources required for consultation with colleagues and education experts; (2) Funds must be made available to faculty for such efforts—a centralized fund for educational improvement in the dean's office can send a powerful message regarding a change in departmental values; (3) Departmental committees, deans, and provosts should consider efforts by faculty who engage students in learning-centered courses as important activities in matters of tenure, promotion, and salary decisions; and (4) Time spent in redesign of introductory courses or in research focused on teaching and learning a discipline should be considered as evidence of a faculty member's productivity as a teacher-scholar.

## ACHIEVING INSTITUTIONAL REFORM

To accomplish such recommendations as listed above, participants explored what individual faculty members could do to advance effective science instruction within the culture of their departments and institutions. They also examined what efforts would be needed by administrators and national organizations to promote effective STEM instruction.

## Influencing Characteristics of Faculty

The circumstances described above led to the concerns of two workshop speakers—Susan Millar, University of Wisconsin, and Elaine Seymour, University of Colorado—both of whom chose to explore why, in the face of the well-documented research-oriented culture of university departments, do some faculty nonetheless become educational innovators? These faculty then model effective instruction and may have direct or indirect influence on colleagues who teach currently and students who may choose to become science faculty, either at the K–12 level or in higher education.

### *Characteristics of Faculty Who Become Instructional Innovators*

*Susan Millar, University of Wisconsin*

In her presentation *Effecting Faculty Change by Starting with Effective Faculty*, Millar outlined characteristics of faculty who are successful in introducing innovative programs of effective STEM instruction. (Refer also to her paper in Appendix A.) During the last decade, Millar has served as external evaluator for numerous STEM education reform efforts. She identified faculty within these programs who showed sincere concern for students' learning and took actions to change the curriculum to address barriers that were interfering with learning. On that basis, Millar classified these faculty members as education innovators, and set out to define their common features. After extended discussions about teaching and learning with her subjects and with other educators whom she used to supplement her analysis, sets of characteristics began to emerge and fell into four topical areas: the change processes, interactions with students and colleagues, learning and teaching, and course materials.

***General qualities.*** Millar first identified general personality features that are characteristic of STEM education faculty innovators but are also characteristic of innovators in general. They tend to be risk takers and hard workers, and individuals who are responsible about commitments, inspired by a sense of mission, savvy and persistent about obtaining resources, and proud of doing a good job for their constituents. She noted that charisma was not necessarily among these characteristics.

***Interactions with colleagues and students.*** Starting with their interactions with students and colleagues, she outlined the defining characteristics specific to STEM education faculty innovators (for further elaboration, see Millar's paper in Appendix A):

- Their identity as scholars does not depend on placing themselves above other faculty members, academic staff, graduate students, or undergraduates.
- They find great pleasure in seeing students learn.
- They view students not as "outsiders" but as less experienced potential peers and thus develop trust within their classrooms.
- They trust undergraduate students and seek ways to give them decision-making power.
- They view graduate teaching assistants as full members of the team and are eager for their input and feedback.

Millar questioned the extent to which faculty could be mentored to learn and develop these characteristics. Alan Kay, Viewpoints Research Institute, Inc., countered by describing his experience with the Defense Advanced Research Projects Agency (DARPA) community, which developed the Internet in the 1960s. Many of his colleagues in the group displayed these characteristics initially, and as the community grew and persisted, new participants took on similar traits as a result, seemingly, of the interaction with the group. Sarah Elgin, Washington University, added that in fact many of the characteristics listed had been described and modeled for her as part of her graduate training at the California Institute of Technology, mentioning in particular the influence of Max Delbruck in the biology department. Millar took note of these examples of developed characteristics as a result of interactions with students and colleagues.

***Attitudes toward learning and teaching.*** Millar cited additional characteristics that pertain to learning and teaching, which she felt faculty could develop more easily with experience:

- They hold the conviction that good teaching demands ongoing creative effort.
- They experience teaching as intellectually exciting and as an opportunity to learn that is no less engaging than the scholarship they pursue in their STEM discipline.
- They understand that learning depends on feeling puzzled, perturbed, and curious, and on tolerating ambiguity.
- They seek to provide course materials and an environment that pushes the students to do the thinking and to "learn to learn."
- They believe that learning entails a constant moving back and forth between "practice" and "beliefs." Effective instruction develops from trying things, reflecting on their effect, trying new

things, and finding ways to interact with colleagues.

- They find that student learning entails reflection through genuine dialogue with senior peers, other students, and one's self.
- They tend to select assessment methods that match their learning objectives, and to use them more to determine their students' preconceptions and concerns and less to grade them, thereby opening up opportunities for feedback.
- They want students to go beyond "knowing that" to "knowing how" and "knowing why."
- They avoid teaching material that not only the students will never use, but the faculty themselves would never use.

***Actions toward institutional change.*** How do such individuals affect the systems within which they are embedded? STEM education innovators, Millar found, try to institutionalize effective educational changes by taking a proactive and pragmatic approach within their spheres of influence. They constantly seek and reflectively use feedback information. Initially, this information is gathered from students and teaching assistants. They reflect on feedback and assess their strategies in discussions with colleagues. To effect greater change, they engage purposively with peer learning communities and, eventually, with networks of people who are engaged in similar efforts and pursuing similar strategies. Millar noted that education innovators often discover the literature of research on learning and teaching and the available networks "in their own time and in their own way"; they often have to develop effective instructional strategies for themselves first.

Anticipating the presentations of upcoming speakers, Millar expressed concern about problems that education innovators face from other faculty, who all too often facilitate students' inclinations to take the "path of least resistance" in obtaining their degrees. Acknowledging Robert Zemsky's reference to the conservatism of universities as enduring institutions (see his paper in Appendix A), Millar commented that colleagues often serve as barriers to the spread of effective instruction within an institution. Because faculty traditionally enjoy freedom and autonomy and cannot be directed to incorporate specific instructional practices, they often limit reform in education or block it. As a group, faculty tend to selectively embrace whatever change will sustain the status quo. However, because of their autonomy, faculty also cannot be stopped when they decide to implement innovative programs of effective instruction.

Millar noted that such opportunities for change are already underway in a number of institutions. She left the participants with two propositions to consider regarding innovators' effect on systems: "As faculty innovators… (1) expand their spheres of influence, they are reshaping and redefining what it is that the ungovernable faculty takes as acceptable norms for educating students…, and (2) The very act of articulating a set of characteristics of the educator innovators helps make visible the ways the innovators among us have contributed to the process of reshaping what it is we take for granted."

***Additional traits proposed by workshop participants.*** After outlining these characteristics, Millar solicited feedback and additional thoughts from the workshop participants to use in revising the characteristics described in her paper (see Appendix A). Several participants[1] offered the following ideas to extend the characteristics presented. Effective instructors respect their coworkers at all levels and build an atmosphere of trust between colleagues, teaching assistants, and students. Given such, they tend to visit other instructors' classrooms to gain ideas from them. They have a willingness to learn. Although they may not have been "born" great teachers, they invest the effort to develop necessary skills, such as communication and collaboration skills, to become effective instructors. Such development can result from dedication to a greater mission to see students learn or through formal mentor programs. The characteristics identified by Millar and other participants do not often exist in entirety in individual faculty members but are present in a continuum among science faculty within effective departments. As a consequence of engagement with instructional improvements, some effective instructors discover gaps in the field of science education research and begin to shift their research responsibilities to disseminate their educational efforts and take steps to justify their education work as scholarship.

### *Innovators' Qualities That Overcome Resistance to Change*

*Elaine Seymour, University of Colorado*

Following Millar's talk, Seymour presented *Barriers to Change: Resistance Is the Normative Mode*. In her talk, Seymour also identified characteristics

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[1] The participants providing ideas included Sarah Elgin, Washington University; John Jungck, Beloit College; Priscilla Laws, Dickinson College; M. Patricia Morse, University of Washington; Robert Olin, University of Alabama; Elaine Seymour, University of Colorado; and Robert Zemsky, University of Pennsylvania.

of classroom innovators, which complemented those of Millar and provided insight into the problems of undergraduate education and appropriate measures for institutionalizing effective instructional strategies. Seymour saw classroom innovators as able to identify and address the dysfunctions of an undergraduate system. The dysfunctions she named were an overreliance on a narrow range of pedagogical tools and an incentive system that emphasizes and provides more rewards for excellence in disciplinary research. The consequences of these priorities, she reported, are: (1) students' focus on memorizing facts for tests, their distancing behaviors such as low attendance rates, and the absence of long-term learning; (2) continuation of science illiteracy; and (3) loss of potential science majors, particularly students of color and women of all races/ ethnicities.

Seymour pointed out that a traditional reaction to these systemic dysfunctions is to blame the students and label them as lazy, ill-prepared, or untrustworthy. Students often appear to be much more engaged in their own social interactions than in a learning community with faculty. Classroom innovators, however, realize that poor student outcomes result in part from systemic effects, and they begin to restructure their curriculum and classrooms. They find ways to reduce the overpacked curriculum and place emphasis on students' responsibility for their own learning. They strive to build a climate of trust. She noted that students might initially demonstrate resistance to these changes because their long-developed and reinforced study habits and learning strategies no longer work well. Colleagues and/or administrators may take note of such student resistance and shift blame to the innovative instructor. Classroom innovators, therefore, look for ways to support their efforts and build an atmosphere of trust and acceptance among teaching assistants, colleagues, and departments.

Seymour reported that innovative educators also enlist researchers, cognitive scientists, and other colleagues in education to provide support for and supply evidence that their intervention is necessary and effective. They document their educational scholarship. They find communities of peers involved in similar education pursuits and strengthen cooperation through face-to-face and online communication, and seek national support for their work through funding and dissemination. They begin to use learning assessment methods that better match their new learning objectives. Seymour identified the Field-tested Learning Assessment Guide (FLAG) as such an assessment (http://www.flaguide.org/). Classroom innovators explore ways to make institutional changes by enlisting senior members of their institutions and promoting review of departmental/institutional tenure criteria and redesign of classroom evaluation instruments.

## Effective Strategies for Departments and Institutions

While individual faculty members can initiate educational innovation as a result of their personal characteristics, the culture of their department and their institution plays a powerful role in enabling or inhibiting the success of such innovation and its expansion to other members of the faculty. This was the issue considered in the presentations of Robert Zemsky, University of Pennsylvania, and a panel of discussants.

### *A Market Approach to Institutional Change*

*Robert Zemsky,*
*University of Pennsylvania*

According to Zemsky, the key to changing institutional practices in ways that reinforce effective teaching is to understand what motivates institutions. In his presentation *On Encouraging Faculty to Pursue Instructional Reform*, Zemsky listed several motivational factors.

***Reasons for change.*** First, he posited that the "faculty guild" will change only if it feels threatened. He defined the guild as membership in a group that offers independence and autonomy. As long as the independence and autonomy of the guild members are respected, they tend to continue traditional and accepted practices. Second, he noted that if students become better consumers of, and take a vested interest in, their education, they will demand change. Unfortunately, students often express the attitude of "just tell me what I need to know" to get a grade instead of recognizing the value of effective learning. Thus, students may need to be trained as consumers. Third, poor results in measured outputs[2] and outcomes incite necessary improvements. Some of the outputs identified by Gloria Rogers, Elaine Seymour, and other workshop participants—such as enrollment numbers, attendance, retention rates, grades, employment statistics, tuition income, funding and contributions, and number of faculty publications—are relatively easy to

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[2] We have chosen to use the terminology summarized in Chapter 3 by Gloria Rogers, Rose-Hulman Institute of Technology, to distinguish between outputs and outcomes. Outputs are indicators, often statistical, whereas outcomes refer to the effects. Outcomes reveal what students have learned, what skills they have gained, how publications were cited, and how resources were used.

collect but may not accurately reflect an institution's shortcomings in teaching.

In that regard, an important outcome that is not as easily assessed (and therefore not often collected) is a measure of student learning. As noted in Chapter 2, evidence is accumulating that traditional lecture-based courses may not result in the expected levels of student learning (Halloun and Hestenes, 1985; Wright et al., 1997; Loverude, Kautz, and Heron, 2002). The realization of failure to educate students as hoped can occasionally have a dramatic impact on instructors and institutions. This is evident in a story related by Zemsky. A science faculty member from a distinguished institution spent two years on the White House staff in the Office of the Presidential Science Advisor. During that time he had the opportunity to talk to two of his own former students who were then congressional staff. During their conversation he realized that, although the students had become accomplished at policy procedures, they did not understand science. He had failed to provide them with the working understanding of science necessary to conduct their jobs as policy makers effectively.

Zemsky cited Clark Kerr's observation (1987) that universities are enduring institutions. In Europe, some seventy have existed in familiar forms with similar functions for centuries. Many see this longevity as evidence of lasting resilience, while others perceive it to be the result of resistance to change. Although Kerr's appeal to the historic university makes clear that change in the academy is slow, Zemsky accepted the challenge to explore in his presentation some of the options that university presidents, deans, and department chairs have at their disposal to encourage and support their faculty in instructional reform. In his paper (see Appendix A), Zemsky outlines several programs that were able to show evidence of both improved student learning and increased retention of students in the discipline.

Illustrating the motivation for some of these reform programs, Zemsky described an effort in the 1980s supported by Dr. Morton Lowengrub, then Dean of Arts and Sciences at Indiana University, to improve mathematics instruction for undergraduates. When asked why he felt such change was needed, Lowengrub referred to mathematics students as an "endangered species." In this case, the motivation to change was fear of extinction; the department was losing students and needed to invigorate the curriculum to retain them. Medical students are not in short supply, Zemsky noted, but many medical schools have adopted new teaching practices simply to keep up with trends in the field. Self-paced, online learning environments and other learner-centered instructional practices have become essential for preclinical courses, as content in the fields has become so extensive that students can no longer absorb and memorize didactically all the information received from instructors.

***Possible plans.*** Based on his observations of reformed programs, Zemsky offered advice to those considering instructional change. He noted that recruitment of celebrated instructors would not likely produce desired changes at the institutional level: "Part of what we need to do [to effect change] is create a market for good teaching. And that's not easy to do, but star teachers aren't the way to do it." He directed workshop participants' attention to two examples of institutions that are considered successful because they have developed their market niche. Hamilton College has gained a widespread reputation among students for its focus on writing and presentation of one's individual self, while Carleton College is perceived as the place to go to prepare for a career in science while living a simple, environmentally focused lifestyle. He also indicated that changing the tenure rules to reinforce and promote effective teaching would have limited impact because so few faculty would be affected.

Instead, according to Zemsky, institutional reform can be achieved more immediately and effectively by acquiring and allocating resources selectively to faculty who are willing to experiment with new, learner-centered modes of instruction. Zemsky cited Barbara Baumstark, an earlier presenter, as an example. She and her colleagues in the Quality in Undergraduate Education (QUE) biology project group at Georgia State University have made great strides in creating explicit learning outcomes for students in their biology program and have also encouraged the department to implement instructional changes designed to achieve those outcomes (see Chapter 2). As Baumstark was already motivated by her participation in the QUE project and dedicated to student learning, she required only modest additional incentives, such as a summer stipend and an extra teaching assistant, to cover the added commitment needed to encourage and mentor her colleagues.

Zemsky concluded by encouraging participants to seek external markets, in addition to grants, for resources and funding. External markets may provide funds for science education research[3] as well as provide places to experiment with instructional practices. Zemsky

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[3] See distinction between science research and science education research made in footnote #4, Chapter 2.

identified three readily available markets that would benefit from science instruction and programs to improve science literacy: primary and secondary schools, corporate groups, and congressional staff. Some university science programs have found "market" support by allying themselves with technology-rich industries. For example, through the San Diego Science Alliance (http://www.sdsa.org/), San Diego State University and the University of California, San Diego, have established partnerships with about forty local corporations that hire graduates at the associate in arts and baccalaureate levels in technical positions.

Following Zemsky's presentation, a panel of three experts with experience in governance and incentives at the institutional/departmental level made brief presentations. These were David Brakke, Jack Wilson, and Herbert Levitan.

### *A Team Building Strategy*

*David Brakke, James Madison University*

Brakke, Dean of the College of Science and Mathematics, set the stage by outlining some of the institutional actions that are required for any type of change to take place. The first step for a leader, usually an administrator of the department, college, or institution, is to begin asking questions about goals. A common vision must be developed so that efforts can be coordinated, effective, and sustained. Step two must be to identify key players. Brakke listed what he considered to be the characteristics of key people: They must have the ability to collaborate in a team, to communicate effectively, to motivate others, to recognize their own strengths and weaknesses, to manage multiple tasks, and to deal with ambiguity. They must be recognized by their peers as action oriented and trustworthy and as having integrity, courage, perseverance, and strategic ability. Although no individual will likely have all of these characteristics, each key person should possess many of them, and teams should be built to encompass all these characteristics by including individuals with different strengths. Equally important is the identification of future leaders to replace people in the teams, since the efforts must be sustained when individuals move on.

Brakke suggested some tactics that institutional leaders might employ to excite individuals to work on such efforts. Starting new programs or expanding existing successful programs often holds attraction for previously uninvolved faculty. The opportunity for collaborative research across departments and perhaps institutions, with colleagues and students, is particularly inviting. Anticipation that such efforts will improve teacher preparation and/or education of the public often appeals to those with altruistic motives.

Once instructional change teams are established, they need to have conversations within and across departments. Direct involvement should come from every level, from faculty to chair to provost. Common interests and needs should be identified through dialogue and opportunities for connections with other disciplines explored.

Michael Zeilik, University of New Mexico, asked the panel members to address how to get individuals in administration, such as chairs and deans, to recognize that a problem even exists. He recalled his own experience with a new department chair who did not believe that a 40 percent decline in students from the department was a problem. Brakke responded that an attitude change would require a number of focused conversations over a period of time.

Educational improvement requires experimentation. For instructional reform, that means making decisions based on evidence from rigorous science education research. Data and evidence should be gathered and analyzed to convince colleagues, boards, and presidents of the need for change and possible appropriate actions. Resources to support science education research and reform efforts can include colleagues, consultants, students, faculty networks, and organizations and institutes such as Chautauqua (http://www.chautauqua-inst.org/education.html), the Science Education for New Civic Engagements and Responsibilities (SENCER) program of the American Association of Colleges and Universities (http://www.aacu-edu.org/SENCER/index.cfm), and Project Kaleidoscope (PKAL) (http://www.pkal.org/).

Brakke added that institutions also need to invest in teaching faculty and offered some ideas. Upon hiring, initial funds should cover start-up costs for teaching as well as research. Institutions can assist faculty in developing their own plans for professional growth. They can support faculty experiences in science education research through assignments—similar to those in science research (e.g., pre- and post-tenure sabbaticals, internships)—at other institutions to build connections and gather ideas to sustain their reform efforts.

### *Top-Down and Bottom-Up Strategies*

*Jack Wilson, UMassOnline*

Wilson drew upon his experiences with many educational improvement projects to discuss how people react to change. Extending Zemsky's comment that change must be top-down, Wilson asserted that it also must be bottom-up. An alliance between individuals at the instructional level and those at the institutional level must exist for change to be sustained. Faculty who are capable of sustaining effective change have the ability to make such alliances because they have earned respect from colleagues through traditional science research or other scholarly endeavors.

To illustrate how people react to change, Wilson described his experience while dean at Rensselaer Polytechnic Institute (RPI). He acknowledged that undergraduate education often operates under an educational equivalent of the old joke about Russian employment contracts ("They pretend to pay us, we pretend to work"), which Wilson modified to: "We pretend to teach them, they pretend to learn. Nobody asks too many questions, everybody is happy."

***From the bottom.*** Wilson pointed out that when such pioneers in educational research in physics as Laws, McDermott, and Hestenes began asking questions about what students learned from traditional courses (Laws, 1997; McDermott, Shaffer, and the Physics Education Group, 1996; Halloun and Hestenes, 1985), nobody, neither faculty, administration, nor students, was pleased to discover that many students were failing to learn much of lasting quality. However that level of distress is what prompted Wilson to develop the "Studio Physics" program at RPI, which pioneered the use of the studio approach to physics instruction (http://www.rpi.edu/dept/phys/education.html). It took eleven years to bring the program to fruition, during which the positions of president, provost, deans, and chairs at RPI were reassigned many times over. Each time new individuals assumed these posts, Wilson had to convince them that Studio Physics was worth continuing. This ongoing justification became part of the reform effort and some deans became strong proponents of the program.

***From the top.*** At one point, the dean of science supplemented the salaries of participating faculty who had become involved, and the effort to expand and adapt the Studio Physics approach for use in other departments was thus supported more readily by faculty within the science division. On the other hand, the dean of engineering was encouraging but offered no tangible support, and the contributions of faculty in that department lagged behind.

The restructuring of physics instruction at RPI had a number of positive effects that helped to sustain the program. Restructuring required more faculty to be involved in the curriculum and many developed a vested interest in the program. As the program was modified to include fewer overall courses, faculty were forced to examine and justify the material they felt was important to include in each remaining course.

Wilson also indicated that their efforts were sustained because they developed an extensive assessment protocol. RPI administrators interviewed and surveyed faculty and students to gather reactions to the studio courses and administered authentic tests of conceptual understanding and problem-solving abilities. To meet state and national interinstitutional standards, traditional midterm and end-of-course exams were used for student grading. These are less sensitive to conceptual understanding, but this had the advantage of demonstrating that students in the program were showing the same or improved performance over students who had been instructed in the original format. The assessments also demonstrated that the studio approach resulted in an improvement in both student and faculty satisfaction with the process. Moreover, developments since have shown that the RPI innovations have had a national impact. Studio Physics has now served as a model for adaptation by other universities, most notably through the Technology-Enhanced Active Learning (TEAL) program of studio physics at MIT (http://research.microsoft.com/features/TEAL.asp).

***In the class.*** As described on its website and noted in Chapter 2 of this report, the defining characteristics of RPI's Studio Physics classes are an integrated lecture/laboratory format, a reduced amount of time allotted to lectures, a technology-enhanced learning environment, collaborative group work, and a high level of faculty-student interaction. The Studio Physics environment employs activities, computer tools, and multimedia materials that allow students to actively participate in their own learning and to construct scientific knowledge for themselves. A high priority is placed on allowing students to learn directly from interacting with the physical world through hands-on activities.

Fewer graduate teaching assistants, though still a sizable number, were assigned to oversee the studio courses and additional undergraduate assistants were brought in. Some of these teaching assistants were initially resistant to the changes to the overall structure of the course, but in the end most, if not all, enjoyed the studio courses, particularly the opportunity to work in teams with faculty as colleagues. The team-teaching approach was effective as it reduced the occurrence of incorrect instruction (i.e., someone in the team would be able to explain material appropriately and correctly to students) and the demands on any individual. When the studio program was fully established, it actually used fewer resources than the traditional format of two faculty members and many graduate teaching assistants per course.

### *Guiding Principles from Granting Agencies*

*Herb Levitan,*
*National Science Foundation (NSF)*

Consideration of a larger social context—including granting agencies, professional societies, institutions, and faculty—was the concern of Levitan, program director of the Division of Undergraduate Education. His presentation was designed to describe NSF's response to the problem of promoting innovation in education. Referring to Zemsky's presentation, Levitan reiterated that for change to occur the following components are needed: agreement that a problem exists, evidence that change will benefit everyone, sufficient time and resources to produce change, and a top-down approach.

Since its inception, the mission of NSF has been to support science research and any activities that contribute to its development. The leadership of NSF has long feared that problems in the educational system could lead to a decline in the pool of future researchers and to a failure to make the general public scientifically literate. To address these possibilities, NSF has taken a top-down approach by combining research and education in their programs and grant offerings. Examples include the Faculty Early Career Development (CAREER) program, the Distinguished Teaching Scholars (DTS) program, Biocomplexity in the Environment (BE): Integrated Research and Education in Environmental Systems, and the Graduate Teaching Fellows in K–12 Education (GK–12) program.

Moreover, NSF has recently mandated that every proposal for scientific research must be reviewed according to two criteria: "intellectual merit" and "broader impact." Examples of the latter category emphasize education: Does the research promote teaching, training, and learning? How will it improve science education? Does it include undergraduate or precollege students as participants? Will the results contribute to educational materials or databases? Ramon Lopez, University of Texas, El Paso, offered an example of the effect of this mandate. He is currently co-principal investigator and director for education at a new NSF-funded science and technology center, the Center for Integrated Space Weather Modeling (CISM; http://www.bu.edu/cism/), where a large number of activities will be education-related and focused on learning in undergraduate education. Lopez believes that the center would not have incorporated these activities if they had not been mandated by NSF.

Levitan considered his own ideas for improving science education to be bottom-up. Levitan proposed that educational change could be achieved by applying, to grant-funded projects that integrate education and research, the same four principles that guide scientific research itself:

- *Be original and take risks.* The best research is that which builds on the efforts of others, explores unknown territory, and risks failure.
- *Provide opportunities for professional development.* Research provides opportunities for personal growth for all who are actively involved. Everyone in the research group, from mentor (faculty project director) to learners (postdocs, graduate students, and undergraduates), has learning goals. Learners gain confidence and stature among peers as they gain proficiency in a field. They engage not only in the research process but also in the integration of the research process and educational process.
- *Provide opportunities for collaboration and cooperation.* Because the most interesting and important problems and questions are usually complex and multidisciplinary, researchers with diverse and complementary perspectives and experiences often collaborate.
- *Evaluate efforts through peer review and peer evaluation.* The expectation of all research is that the outcomes will be communicated and available to an audience beyond those immediately involved in the research activity. Efforts should be disseminated so others can critique them. That can occur via peer-reviewed publication or commercial products. The value of the research will then be measured by the impact—how widely cited or otherwise used—of its product.

Levitan emphasized that dissemination of products (e.g., course materials, publications, websites) should be the goal at the outset of any educational program. He concluded by restating that researchers, whether funded by NSF, NIH, or private foundations, should consider the development of education projects in the same ways they develop science research projects: by reading the literature and consulting with colleagues to determine what is already known, and then moving beyond that with a novel approach to the problem.

### *Effective Faculty Professional Development*

Responding to Levitan's charge to integrate research and education, Lillian Tong, University of Wisconsin, posed questions about what is meant by "teaching as research" and what are the criteria by which education research should be judged. The former is a question posed frequently in the literature of science education (Boyer, 1990; Shulman, 1990; NRC, 2002c, 2003) and one that Tong recalled is heard over and over again by staff at the newly launched Center for the Integration of Research, Teaching, and Learning (CIRTL) at the University of Wisconsin (http://www.wcer.wisc.edu/publications/news/research_notes/articles/cirtl_center.asp).

A university-level professional development program that aims to change the definition of the teaching process, CIRTL's emphasis is on "teaching as research": University of Wisconsin STEM faculty are expected to approach teaching in the same evidence-based manner that they conduct their research, which includes hypothesizing, implementing, observing, analyzing, and improving. The efforts of CIRTL encourage instructors to learn about teaching strategies from evidence-based work, observe and assess the effects in their own classrooms, and apply findings to improve their teaching practices. Levitan added a twist to this assessment by suggesting that, just as one can undertake research in unknown areas of science, an instructor can teach an unfamiliar subject and thereby demonstrate to students how to learn something new. In response to Tong's second question, Levitan concluded that criteria for judging the quality of science education research should be established by editorial boards of appropriate journals.

The achievements of CIRTL, as well as those of other programs for the professional development of science faculty, can have far-reaching implications. Several workshop participants argued for placing science courses designated for preservice teachers within science departments rather than schools of education because effective teaching of undergraduate science, especially for these students, requires both specialized content knowledge and appropriate instructional strategies. If preservice teachers are taught effectively by science faculty, this could break the cycle noted in Chapter 2 by Bruce Alberts, President of the National Academy of Sciences, of incoming college students who have inadequate science backgrounds because they were educated by K–12 teachers who teach how they were taught in their own undergraduate science courses and who, therefore, never developed a true feel for the nature of science. Bonnie Brunkhorst, California State University, San Bernardino, and Lillian McDermott, University of Washington, agreed that such science preparation should be the responsibility of science departments, but they encouraged continued conversations among science faculty and their colleagues in education departments (or schools) on how to best meet the needs of preservice teachers in introductory science courses.

## SUMMARY

The following is a summary of the major ideas voiced by workshop participants regarding the impact on educational change of personality traits of individual faculty and the characteristics of organization, governance, and incentive structures within departments and institutions. The main goals for improving science instruction are to increase student conceptual understanding of the science disciplines and to enhance their scientific reasoning skills. Among the barriers to achieving these goals are two systemic dysfunctions: an overreliance by faculty on a narrow range of pedagogical tools and an incentive system that rewards excellence in disciplinary research but not in teaching.

According to an ethnographic study by one of the presenters, faculty that are instructional innovators are usually individuals who find great pleasure in seeing students learn, view students not as "outsiders" but as less experienced potential peers, and who experience teaching as an activity that is just as intellectually exciting and engaging as the scholarship they pursue in their STEM discipline. Because of these characteristics, they seek to provide course materials and an environment that pushes the students to do the thinking and to "learn to learn," and they tend to use assessment methods more to determine their students' preconceptions and concerns and less to grade them, thereby opening up opportunities for feedback.

At the institutional and departmental level, strategies commonly used in market analysis may be beneficial in this effort. University administrators have a number of options at their disposal in promoting instructional change, such as acquiring funds dedicated to educational reform and publicly announcing that such resources are available; arranging for pre- and post-tenure mentoring in effective teaching (in collaboration with the school or college of education if appropriate); establishing a top-down and bottom-up department-wide culture in support of effective instruction; selectively allocating funds to key faculty who are willing to try new, learner-centered modes of instruction; offering summer stipends and sabbatical leaves for new course development, extra teaching assistants, and reduction of teaching loads during course improvement; and establishing a policy that every course in a department must be designed to achieve specific, predetermined learning outcomes that include both conceptual understanding of the subject and cognitive process skills.

At a national level, workshop participants considered what granting agencies such as the NSF can do to promote educational change by combining research and education in their policies, programs, and grant offerings. NSF currently offers some programs to promote educational change, including the Math and Science Partnership program, the Learning and Teaching Centers, the NSF Director's Award for Distinguished Teaching Scholars (DTS), the Faculty Early Career Development (CAREER) program, Biocomplexity in the Environment (BE): Integrated Research and Education in Environmental Systems, and the Graduate Teaching Fellows in K–12 Education (GK–12) program. NSF has recently mandated that every proposal for scientific research must meet criteria for both "intellectual merit" and "broader impact." The latter criterion requires that proposals demonstrate that the research will promote teaching, training, and learning; improve science education; include undergraduate or precollege students as participants; and contribute to educational materials or databases.

# 5

# General Discussion

In preparation for organizing their ideas into a framework of criteria and benchmarks, participants spent much of the concluding discussion of the workshop identifying qualities that institutions or departments could use to measure the effectiveness of courses and educational programs. One such quality, for example, would be a focus on students' success in learning the skills of scientific reasoning and information gathering. Another measure would of course be students' understanding of science content. As noted by Richard McCray, University of Colorado, workshop participants had already identified two other critically important learning outcomes: gains in students' demonstrated abilities to learn on their own and to recognize when they have learned.

To achieve these desired learning outcomes, faculty engaged in effective teaching would employ some of the instructional strategies described in Chapter 3, and be judged by their success in utilizing such strategies. To further the pursuit of effective instruction, institutions and departments would form education leadership groups such that faculty could share teaching experiences and resources with colleagues and become familiar with the literature of education research. Communication feedback loops and dissemination mechanisms were identified as important aspects of promoting effective teaching at institutional and departmental levels (see Chapter 4). These ideas are also elaborated in some detail in the National Research Council (NRC) report *Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics* (2003).

Several participants pointed out that departments should support faculty's collaboration outside their own institutions, such as faculty participation in workshops to educate them on effective instructional practices and dissemination of instructional experiences through professional societies and other regional and national organizations. Many participants felt that developing support structures within science departments for effective research in science education was an important step toward improving science education.

This chapter summarizes participants' discussions in regards to the institutional or departmental qualities listed above.

## FOCUS ON STUDENTS' SKILLS FOR LEARNING ON THEIR OWN

How does one measure gains in students' abilities to learn on their own? McCray emphasized that introductory science courses need to focus on students' learning skills of scientific reasoning and information gathering as much as on science content, and on helping students take greater responsibility for their own learning. The content in science fields is growing so rapidly, he noted, that it has become virtually impossible to transmit it all. In addition, the paths chosen by students are very diverse; the specific content needed by a student who will go on to medical school is different from the content needed by someone who will become a biologist or a K–12 teacher.

Thus, teaching the skills necessary to learn on one's own is most important. The faculty's role is to help students understand the skills necessary to learn on their own—to seek out resources, make decisions based on evidence, assess one's understanding of these skills and abilities, and apply these skills to relevant content—and to promote students' taking responsibility for their own learning. Anton Lawson, Arizona State University, added that instructors should be aware of the reasoning skills and abilities students have when they enter the classroom and the need to focus on developing those to a higher level throughout the course. Students should also leave science courses with an appreciation and understanding of the nature of science.

## INSTITUTIONAL SYSTEMS THAT PROMOTE EFFECTIVE INSTRUCTION

Ramon Lopez, University of Texas at El Paso, acknowledged these were important learning objectives, but suggested that efforts focused only on individual instructors are insufficient to bring about the required level of change. He called on Jack Wilson, UMassOnline, to describe further how he had initiated change to improve education at the institutional level at Rensselaer Polytechnic Institute (RPI).

### Administrative Support, Common Vision, and Effective Strategies Create Success

Wilson recalled that the transformation was catalyzed by four intersecting forces: the vision of RPI's new president, the retirement of faculty members who had been responsible for the traditional curriculum in introductory physics, the fact that a number of faculty had become frustrated with their unsuccessful efforts in teaching the introductory courses, and the convenient availability of the new Studio Physics program as an alternative. Physics faculty members became supportive of the reform efforts when they discovered that they could work with students in smaller and less intimidating groups, that the new structure required less preparation, that students demonstrated better understanding of concepts, and that they enjoyed the teaching experience more.

Michael Zeilik, University of New Mexico, suggested that medical and law schools could serve as examples of institutions that have demonstrated successful innovations by changing not just selected courses but their entire curricular structure and teaching vision. For example, the University of Texas Medical Branch has virtually abandoned traditional lecture courses. On its website the center now states the following as its three most important educational principles: "Learning should be active, not passive"; "Most of the basic science facts and information can be learned in the context of clinical problems, an approach that highlights relevance for basic science knowledge"; and "Faculty time should be used to introduce, to clarify, to discuss, to stimulate, to guide, to impart and imbue the student with enthusiasm for the topic at hand" (http://meded.utmb.edu/faq/principles.htm).

According to Robert Zemsky, University of Pennsylvania, some medical schools place great emphasis in their new curricula on information transfer, to the extent that their publications speak in terms of teaching and developing skills that resemble those of librarians. New physicians are trained to know how to ask the question, how to find the answer through resources, and how to determine the appropriateness of the answer within known constraints. Such changes reflect the recognition in recent decades that the goals of medical education must change from teaching science to equipping students to learn science.

Katayoun Chamany, Eugene Lang College, wondered if successful reforms might result from new efforts by institutions to think more about learning outcomes. When faculty begin to envision the environments and activities that their students will experience in the future, they may feel the responsibility to offer subject matter that is relevant to the students and to provide capabilities and skills needed for them to function effectively in these environments and activities. Expanding on the need for relevance, Chamany also pointed out that when instructors choose subject matter that is useful and has a direct bearing on students' lives, students are more likely to assimilate the facts, concepts, and skills being taught.

She promoted the approach that is taken by programs such as Science Education for New Civic Engagement and Responsibilities (SENCER) of the American Association of Colleges and Universities (http://www.aacu-edu.org/SENCER/overview.cfm), which offers program modules and case studies as techniques for connecting subject matter to students' interests. Referring to the report *Leadership Reconsidered* by the W.K. Kellogg Foundation (2000), David Gosser, City College of New York, added that if students are treated as participants (or leaders at some level) in course design and empowered to offer input on content and teaching methods, as is common in the Peer-Led Team Learning workshop model (http://www.pltl.org), they are likely to perceive their education experience as relevant.

### Lack of Administrative Support and Rewards Triggers Failure

Turning away from successful reforms at institutions, Clyde Herreid, State University of New York at Buffalo, voiced concern over failed efforts at reform. He noted that problem-based learning programs that began with great fanfare have not been sustained at some medical schools. He attributed many of these failures to lack of administrative buy-in and nonexistent reward systems. The efforts of small, enthusiastic faculty groups were lost for lack of appropriate administrative support. Lack of success is not limited to medical school endeavors.

Carl Wieman, University of Colorado, pointed out that the current system in science departments rewards discovery-based and applied research with little consideration given to teaching responsibilities. Science faculty are encouraged to devote most of their time and energy to their research projects because funding and rewards are directed toward research. In a recent meta-analysis of 122 studies of standards-based school reform programs between 1991 and 2001, Chatterji (2002) found that "these reforms have been largely unfocused and nonsystemic in design and have thereby failed to help individual schools, school systems, and statewide systems to develop in the directions that are consistent with the mission of the reform movement" (p. 345).

### Research Defines Need and Direction

Strengthening his focus on strategies that would apply at the national and institutional level, Lopez stated that it is important for researchers and change agents to examine both the successes and failures of institutional reform. He cited the calculus reform effort as one in which panels of objective observers have provided carefully balanced reviews that describe both successful aspects and those in need of improvement (e.g., NRC, 2002b, pp. 246–249).

McCray emphasized a point that had been made several times during the workshop, that efforts to improve instruction should be targeted especially at large introductory science courses where the need for change is often greatest.

#### *Support Systems for Science Education Research Requested*

Paula Heron, University of Washington, suggested that one way to promote effective teaching at the institutional/departmental level is to hire and find ways of supporting faculty whose research focuses on the learning and teaching of the science discipline represented. Such faculty should be able to thrive, and receive recognition, in traditional research departments. M. Patricia Morse, University of Washington, agreed that an institutional influence on improving education is to advance a structure that accepts the scholarship of science education research as equivalent to discovery research conducted in science fields. She also agreed that some science faculty need to be involved in science education research, and they need to be based in science departments. Many participants saw the value of carrying out science education research within science departments, in the context of a science discipline.

However, David Brakke, James Madison University, raised the question of whether a traditional science department could support a "critical mass" of faculty whose scholarship lies in science education research (i.e., a large enough group to sustain high-quality research on teaching and learning).

Currently, noted Lawson, in some departments individual faculty members persist by collaborating with colleagues at other institutions engaged in similar research and by earning respect within their own department or institution for the external grant support that they receive and their reputation as education researchers. Lillian McDermott, University of Washington, pointed out that the number of faculty in a department with a focus on science education research would depend on the range of programs and research projects undertaken in the department. Different numbers of individuals would be needed to sustain teacher education programs, curriculum development efforts, or large or small research projects on learning and teaching of the discipline subject matter.

### *Role of Faculty in Science Education Research Addressed*

Throughout the workshop, participants recognized different roles of science faculty with regard to teaching and research. Three kinds of roles sparked repeated discussions: scholarship taken in science research, scholarship taken in science education research, and efforts aimed at scholarly teaching (by which most participants meant instruction that is directed at specific learning goals, relies on research about how people learn, and employs ongoing evaluation of learning as well as teaching). One question raised by the above discussion was how appropriate and feasible is it for faculty in science departments to devote their scholarship to science education research rather than—or in addition to—science research? Continued discussion set out to define the characteristics of individuals who assume these different roles and to determine how both faculty whose scholarship lies in science research and those whose scholarship lies in science education research can engage in scholarly teaching.

Earlier in the workshop, Wieman had remarked that the characteristics of education innovators, presented by Susan Millar, University of Wisconsin, are similar to those of many successful scientists. Several participants had agreed with his remarks. Zemsky commented that it is important to define the distinction between a research leader and an educational leader. He wondered if one person could play both roles. Referring to examples provided by Millar and Elaine Seymour, University of Colorado, Zemsky pointed out that even when one person has assumed both leadership roles, the roles are usually undertaken at separate stages of that person's career.

Zemsky's remarks spurred a number of comments from other participants. James Serum, SciTek Ventures, noted that he agreed with Wieman's observation and added the important distinction that education innovators feel personally rewarded when they observe students understanding new concepts. Successful researchers feel satisfaction when they make discoveries in their own laboratories. Priscilla Laws, Dickinson College, echoed Serum's observation and took the opportunity to clarify the terminology regarding effective teaching and research in teaching. Certainly, innovators in education and innovators in science are likely to have similar qualities, but they usually do not possess, by nature of their choice of scholarship, the same passions and talents. Most faculty members with research appointments are expected to conduct research and also to teach.

Referring to her own dean's distinction between teaching and research, Laws noted that every faculty member at her institution is responsible for effective teaching within his or her own classroom. But those efforts in the classroom do not constitute research, or scholarship, unless they are extended to include evaluation, written articles, and dissemination beyond the institution (Boyer, 1990; Glassick, Huber, and Maeroff, 1997; NRC, 2003). Insofar as such an effort adheres to agreed principles of scientific research (Shulman, 1997; NRC, 2002c), the distinction between those who have been called education innovators and those who have been called successful scientists or researchers is only their choice of research fields; they are both in fact researchers (scientists).

McCray noted that common characteristics of the two sets of faculty are the ability to disseminate information and to collaborate with colleagues. McCray also pointed out that instructors who are recognized to have effective courses or programs make conscious efforts to collaborate with their colleagues and provide them with resources about teaching. Assessment of learning objectives and actual learning outcomes is an ongoing process within their courses as well as within disciplinary programs, departments, and institutions that they can influence.

Wieman conceded that developing structures for effective research in science education may be an important step toward improving science education, but he felt that the more important issue was to discuss efforts necessary to develop and train science faculty who are not likely to be involved in education research but who are nonetheless effective science instructors. He drew attention to the fact that the workshop's focus was on improving science education, not establishing science education research.

Robert DeHaan, National Academies, questioned whether science education research would have an impact in the near future in terms of disseminating effective instructional practices and advancing professional development for young science faculty. Heron and McDermott responded that they are currently conducting research into this question in their physics department at the University of Washington (see McDermott's paper in Appendix B). McDermott pointed out that an important issue for the Physics Education

Group is to discover the connections between science education research and instructional practices. She noted that developing reliable answers to such questions requires a process of pre- and posttests, iterations, and testing in other places, and therefore takes time. After their many years of research, they presently conduct workshops for science faculty to educate them on effective instructional practices, covering aspects of course design based on *Physics by Inquiry* (McDermott, Shaffer, and Rosenquist, 1996). Heron offered that faculty could save time and effort while improving science education by adopting materials developed by those engaged in science education research. In their workshops, they encourage participants to determine whether the materials are appropriate and useful for their institutions.

Heron also identified a national program, funded by the National Science Foundation and the American Association of Physics Teachers, that is exposing young physics faculty to recent research on the learning of physics and the implications such information has on instructional practices (American Association of Physics Teachers, 2001). Heron's suggestions echoed Millar's findings (described in Chapter 4) that effective instructors find teaching an ongoing creative effort, intellectually exciting, and an opportunity to learn, try new things, and interact with colleagues.

## IMPERATIVE FOR COLLABORATION AND FEEDBACK

The above discussions indicate that collaboration among faculty members and administrators, dissemination of science education research, and ongoing assessment and reevaluation of educational efforts are key in promoting effective instruction at the institutional level. Morse remarked that institutions should encourage faculty to strive for a higher level of collaboration through their professional societies; all science faculty should continually receive and reevaluate the information they need to be effective teachers through workshops, professional meetings, and journal papers. In agreement, John Jungck, Beloit College, added that learning about the existing knowledge base in science education also provides opportunities for faculty members to appreciate problems that exist in the field and to discover new techniques and programs that they can use in their own institutions. Jungck acknowledged that what has been discovered with regard to education in one science field likely has applications to other science fields.

McCray took this idea one step

further by suggesting that faculty should be encouraged to develop leadership groups on campuses with members representing different departments. The goal of these faculty groups would be to share educational experiences and take steps to expand effective instruction throughout their campuses and other institutions. Jungck asserted that in addition to formulating new research questions appropriate for the improvement of science education, faculty leadership groups would also have the opportunity to examine current science education research in ways that recognize the connections between disciplines.

## SUMMARY

The following is a summary of the major ideas voiced by workshop participants during this final wrap-up session. For the most part, they mirror and underscore what was expressed in the earlier sessions.

Workshop participants identified qualities that institutions or departments could use to measure the effectiveness of courses and educational programs. Administrators and faculty members share a common vision that focuses their efforts on students' learning and helping students take greater responsibility for their own learning. Institutional systems reward faculty for their efforts to improve teaching and encourage collaboration. The value of education research that adheres to accepted principles of scientific investigation is respected and acknowledged. Interdepartmental education leadership groups are formed to share teaching experiences and resources with colleagues and become familiar with the literature of education research. Faculty continually seek feedback from students and colleagues about their teaching and use that information to reevaluate and improve their performance. Faculty and administrators promote change in STEM education beyond their own institutions through their professional societies and other regional and national organizations. They may contribute nationally by applying strategies of effective programs at their own institutions, disseminating information about their own courses, both successes and failures, and working with colleagues to formulate research questions dealing with teaching and learning.

# 6

# Epilogue

On November 19–20, 2002, fifty-one invited participants from the fields of science, technology, engineering, and mathematics (STEM), postsecondary education, and education policy, along with National Research Council (NRC) staff and other interested parties attended a two-day workshop in Washington, D.C. at the National Academies. Participants and presenters were asked to explore three related issues: (1) how appropriate measures of undergraduate learning in STEM courses might be developed; (2) how such measures might be organized into a framework of criteria and benchmarks to assess instruction; and (3) how departments and institutions of higher learning might use such a framework to assess their STEM programs and to promote ongoing improvements. Participants covered a diverse set of topics and questions in addressing these issues. This document is not intended as a consensus report of the participants, and the steering committee provides no specific recommendations. Rather, the workshop was intended as an information-gathering activity by the Committee on Undergraduate Science Education (CUSE).

Several overriding concerns are highlighted here because workshop participants raised them numerous times. This Epilogue focuses especially on those topics and questions that call for further investigation, because addressing them more fully could have an important influence on improving education in all of the science disciplines and at all levels. The concerns addressed during the workshop were as follows.

## THE IDENTIFICATION OF STUDENT LEARNING OUTCOMES

In response to the first framing issue about developing measures of student learning, several speakers and discussants including Brian Reiser, Northwestern University, and Gloria Rogers, Rose-Hulman Institute of Technology, argued that in preparing an effective science course, faculty must identify explicit, measurable learning objectives or outcomes (defined as what students need to know and be able to do by the end of each unit of instruction). A critical question was whether learning outcomes should be limited to a list of content terms, or—as proposed by one of the workshop speakers—should they consist of a framework of facts, central concepts, reasoning skills, and competencies such as the skills needed to think critically, an understanding of what constitutes evidence, and the ability to design a simple experiment?

## THE RECOGNITION OF STUDENTS' PRECONCEPTIONS AND THEIR RESISTANCE TO CORRECTIVE TEACHING

With reference to issue 2, Paula Heron, University of Washington, described evidence that students' preconceptions may be resistant to change by traditional didactic instruction such as lecturing.  She demonstrated that students come to any topic with prior beliefs and conceptions that are often incomplete or erroneous, and that require carefully designed, specific measures to correct. Participants repeatedly acknowledged that judging an instructor's knowledge and skill in applying such measures should be among the criteria for assessing instruction and for evaluating the extent to which instructors have at their command a variety of teaching strategies, in addition to lecturing, that are able to elicit a correct and deeper understanding of the subject on the part of students. According to the evidence reviewed, lecturing promotes memorization of factual information while more effective instruction that helps students gain functional knowledge requires teaching methods that assist them in explicitly reconciling their preconceptions with new information.

## THE MEANS TO EVALUATE INSTRUCTION

Further in response to issue 2, participants discussed the need for better assessment tools for evaluating course design and effective instruction. Anton Lawson, Arizona State University, emphasized results showing that the Reformed Teaching Observation Protocol (RTOP) could serve as a useful instrument for judging some aspects of teaching, and recommended that this tool might serve as a model for an expanded instrument for that purpose. An evaluation instrument such as RTOP could be improved, suggested several participants, by including criteria for evaluating instruction that focus more on its success in eliciting defined learning outcomes among students.

Participants recognized that research on assessing and delivering undergraduate instruction is urgently needed, especially studies of how to improve teaching of large classes. Investigations in every subject area are necessary to identify students' difficulties with specific concepts in each discipline. Research is also needed to find effective combinations or sequences of problem-solving, inquiry-based and didactic instructional practices to achieve student understanding of both basic concepts and the processes of scientific thinking. Arguments were presented by participants that much of that research could be done by scientists who are thoroughly grounded in the discipline, or by collaboration between such scientists and colleagues in education research.

## THE EXISTENCE OF MODEL PROGRAMS

Seeking models from which to extract traits to include in a set of criteria and benchmarks for evaluating instructional programs, workshop participants drew upon their own knowledge and experience to identify programs and curricula that are reputed to represent models of various forms of effective instruction. In the absence of a systematic national survey, those cited repeatedly were Biology Guided Inquiry Learning Environments (BGuILE), New Traditions, Peer-Led Team Learning (PLTL), Physics by Inquiry, Studio Physics, Workshop Physics, Problem-based Learning (PBL), and Case-Study Teaching. These programs are all characterized by some or all of the following traits: they have as their major aim to elicit specific factual, conceptual and cognitive learning outcomes on the part of students; they recognize that students have diverse learning styles and that they learn in different ways under different circumstances; they provide experiences for students to develop functional understanding of science concepts by using knowledge in investigations and problem-solving exercises and by making interdisciplinary connections; they promote students' ability to work cooperatively, to communicate orally and in writing, and to develop independent learning skills; and they address the relevance of both science content and the processes of science to students' lives.

## THE CHARACTERISTICS OF EFFECTIVE TEACHERS

Faculty who become instructional innovators and effective teachers share certain characteristics such as their expressions of equal respect toward academic staff, graduate students, and undergraduates, their command of a variety of instructional strategies that promote students' conceptual understanding, and their ability to apply knowledge in new situations. These findings of an ethnographic study by Susan Millar, University of Wisconsin, served as a central point of discussion for the participants with reference to issue 3.

## INSTITUTIONAL ORGANIZATION AND INCENTIVES THAT PROMOTE CHANGE

One element of issue 3 that participants focused on was whether opportunities and incentives for faculty to become familiar with different modes of instruction are sufficient to provoke needed changes in teaching? In responding to this question, several speakers and participants including Robert Zemsky, University of Pennsylvania, Herb Levitan, National Science Foundation, and Jack Wilson, UMassOnline, addressed the need to change the entire culture of higher education by a "top-down and bottom-up" approach. In the present structure of most institutions of higher learning, especially in research-intensive universities, incentives for faculty to learn new teaching methods are few.

Some of the strategies by which presidents, deans, and department chairs might encourage such cultural change included publicly announcing a fund earmarked for the support of faculty efforts to develop new courses; rewarding faculty efforts to improve instruction by allotting release time, summer stipends, or sabbatical leave; modifying promotion and tenure policies in ways that motivate faculty to spend time and effort on developing new teaching methods or redesigning courses to be more learner centered; providing instruction and mentoring for graduate students, postdoctoral fellows, and faculty in effective teaching practices; and recognizing time spent in the redesign of introductory courses or in research on teaching and learning the discipline as evidence of a faculty member's productivity as a teacher-scholar.

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# Appendix
# A

# Commissioned Papers

# Using the RTOP to Evaluate Reformed Science and Mathematics Instruction[1]

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## INTRODUCTION

The Arizona Collaborative for Excellence in the Preparation of Teachers (ACEPT) Program is a National Science Foundation (NSF)-sponsored program aimed at improving undergraduate science and mathematics instruction at Arizona State University (ASU) and in the surrounding community colleges. The primary reform mechanism has been summer workshops in which college faculty experience reformed teaching methods and then attempt to implement those methods in their courses. The reformed methods are based on the principles of effective teaching introduced by the American Association for the Advancement of Science (AAAS) in *Science for All Americans* (1989). In turn, the AAAS teaching principles (see Box A-1) are based on learning theory derived from years of cognitive research. That theory posits that learning results from active, learner-centered inquiry in which students construct new concepts and conceptual systems by connecting new information and concepts to what they already believe. Further, effective learning often requires restructuring, or even discarding, previous concepts and beliefs when they prove incompatible with, or contradictory to, new evidence and new concepts (e.g., Alexander and Murphy, 1999).

The ACEPT program has attempted to incorporate reformed teaching methods into several courses for nonmajors and majors. These include

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[1] Based in part on Lawson et al. (2002).

## BOX A-1 Principles of Effective Teaching

- *Teaching Should Be Consistent with the Nature of Scientific Inquiry:*
  Start with questions about nature; Engage students actively; Concentrate on the collection and use of evidence; Provide historical perspectives; Insist on clear expression; Use a team approach; Do not separate knowing from finding out; Deemphasize the memorization of technical vocabulary.
- *Teaching Should Reflect Scientific Values:*
  Welcome curiosity; Reward creativity; Encourage a spirit of healthy questioning; Avoid dogmatism; Promote aesthetic responses.
- *Teaching Should Aim to Counteract Learning Anxieties:*
  Build on success; Provide abundant experience in using tools; Support the role of girls and minorities in science; Emphasize group learning.
- *Science Teaching Should Extend Beyond the School.*
- *Teaching Should Take Its Time.*

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SOURCE: AAAS (1989, pp. 200–207). Reprinted with permission of Oxford University Press.

*Introduction to Physical Geology*, *Fundamentals of Physical Science, Theory of Elementary Mathematics, Patterns in Nature, The Living World, University Physics,* and *Methods of Teaching Biology*. Evaluation has focused on two central questions: What effect, if any, have the summer workshops had on participant faculty's use of reformed teaching methods? And what effect, if any, does the use of reformed methods have on student achievement? The following sections describe evaluation efforts in five courses and a brief evaluation of the teaching methods used by some recent graduates as they begin their elementary, middle, or high school teaching careers.

### COMPARING REFORMED INSTRUCTION WITH STUDENT ACHIEVEMENT

*Fundamentals of Physical Science (PHS 110)* is an introductory course designed specifically for preservice elementary school teachers. A test of physics concepts, developed by course instructors and the ACEPT evaluation team, was administered to four experimental and two control *PHS 110* sections at the beginning and again at the end of a recent semester. A member of the ACEPT Program at ASU (the principal investigator) taught one experimental section. Community college instructors who had participated in an ACEPT summer workshop taught the other three experimental sections. Importantly, these instructors were not selected at random. Rather, they were selected because they exhibited considerable variation in the extent to which they appeared to be embracing the reformed methods during the summer workshop. Community college instructors who had not participated in a summer workshop taught the two control sections.

Instructional methods were evaluated using an ACEPT-developed instrument called the Reformed Teaching Observation Protocol (RTOP). The RTOP consists of 25 statements about the extent to which reforms are incorporated into instructional practice (see Box A-2; details available at http://ecept.net/rtop/). Each statement is scored on a 0–4 "Never Occurred" to "Very Descriptive" scale. Thus, the RTOP allows observers to rate instruction on a 0–100 scale. Details of RTOP development and administration can be found in Sawada (1999), Sawada et al. (2000a), and Sawada et al. (2000b). Estimates of inter-rater reliability have been obtained using seven trained evaluators as they observed several math and science instructors and independently scored several lessons. Inter-rater reliabilities have been high as evidenced by the following pairs of independent observations and respective coefficients (16 pairs, r = 0.94; 4 pairs, r = 0.99; 7 pairs, r = 0.97; 6 pairs, r = 0.94; 5 pairs, r = 0.93; 9 pairs, r = 0.90).

Mean RTOP scores for each *PHS 110* instructor and the respective normalized pre- to posttest achievement gains (i.e., percent gain/percent gain possible) for each instructor's students (n = number of students in each section) were calculated. Among the experimental sections, mean RTOP scores varied from 27 to 73. Mean RTOP scores for the two control instructors were 28 and 37. Normalized achievement gains varied from 0–57 percent across all sections. Importantly, mean instructor RTOP scores correlated strongly with student achievement gains ($r = 0.88$, $p < 0.05$). This result supports the claim that reformed teaching methods promote higher achievement. Figure A-1 shows instructor RTOP scores and normalized gains on the test of physics concepts for ACEPT (experimental) and control sections.

*Theory of Elementary Mathematics (MTE 180)* is an introductory course designed specifically for preservice elementary school teachers. Four *MTE 180* instructors participated in the initial ACEPT summer workshop. Subsequently, one of those instructors (from ASU) helped two additional ASU *MTE 180* instructors develop reformed teaching methods. During a recent

## BOX A-2 Reformed Teaching Observation Protocol (RTOP)

### Lesson Design and Implementation

(1) The instructional strategies and activities respected students' prior knowledge and the preconceptions inherent therein.

(2) The lesson was designed to engage students as members of a learning community.

(3) In this lesson, student exploration preceded formal presentation.

(4) The lesson encouraged students to seek and value alternative modes of investigation or problem solving.

(5) The focus and direction of the lesson was often determined by ideas originating with students.

### Content

*Propositional Knowledge*

(6) The lesson involved fundamental concepts of the subject.

(7) The lesson promoted strongly coherent conceptual understanding.

(8) The instructor had a solid grasp of the subject matter content inherent in the lesson.

(9) Elements of abstraction (i.e., symbolic representations, theory building) were encouraged when it was important to do so.

(10) Connections with other content disciplines and/or real world phenomena were explored and valued.

*Procedural Knowledge*

(11) Students used a variety of means (models, drawings, graphs, concrete materials, manipulatives, etc.) to represent phenomena.

(12) Students made predictions, estimations, and/or hypotheses and devised means for testing them.

semester, six sections of *MTE 180* participated in a study. Three ACEPT-influenced instructors taught three sections at ASU and control instructors taught three sections (one at ASU and two at a nearby community college). A test measuring concept understanding, number sense, and computational skills was administered at the beginning and again at the end of the semester. During the semester, each instructor was evaluated at least twice using the RTOP.

Instructor mean RTOP scores and student posttest scores on the concept-understanding test were calculated for each section. Instructor mean RTOP

(13) Students were actively engaged in thought-provoking activity that often involved critical assessment of procedures.

(14) Students were reflective about their learning.

(15) Intellectual rigor, constructive criticism, and the challenging of ideas were valued.

### Classroom Culture

*Communicative Interactions*

(16) Students were involved in the communication of their ideas to others using a variety of means and media.

(17) The instructor's questions triggered divergent modes of thinking.

(18) There was a high proportion of student talk and a significant amount of it occurred between and among students.

(19) Student questions and comments often determined the focus and direction of classroom discourse.

(20) There was a climate of respect for what others had to say.

*Student/Instructor Relationships*

(21) Active participation of students was encouraged and valued.

(22) Students were encouraged to generate conjectures, alternative solution strategies, and ways of interpreting evidence.

(23) In general, the instructor was patient with students.

(24) The instructor acted as a resource person, working to support and enhance student investigations.

(25) The metaphor "instructor as listener" was very characteristic of this classroom.

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NOTE: Each item is scored on a 0–4 "Never Occurred" to "Very Descriptive" scale.

SOURCE: Lawson et al. (2002, p. 390). Reprinted with permission of National Science Teachers Association.

scores and student posttest scores were found to correlate strongly ($r = 0.94$, $p < 0.001$). Mean RTOP scores and normalized gains also correlated strongly ($r = 0.86$, $p < 0.001$). A very strong positive correlation was also found between instructors' mean RTOP scores and student posttest number sense scores ($r = 0.92$, $p < 0.001$). These results further support the claim that reformed teaching methods improve student achievement. As predicted, no relationship was found between instructors' mean RTOP scores and student posttest performance on the computational skills section. This result was

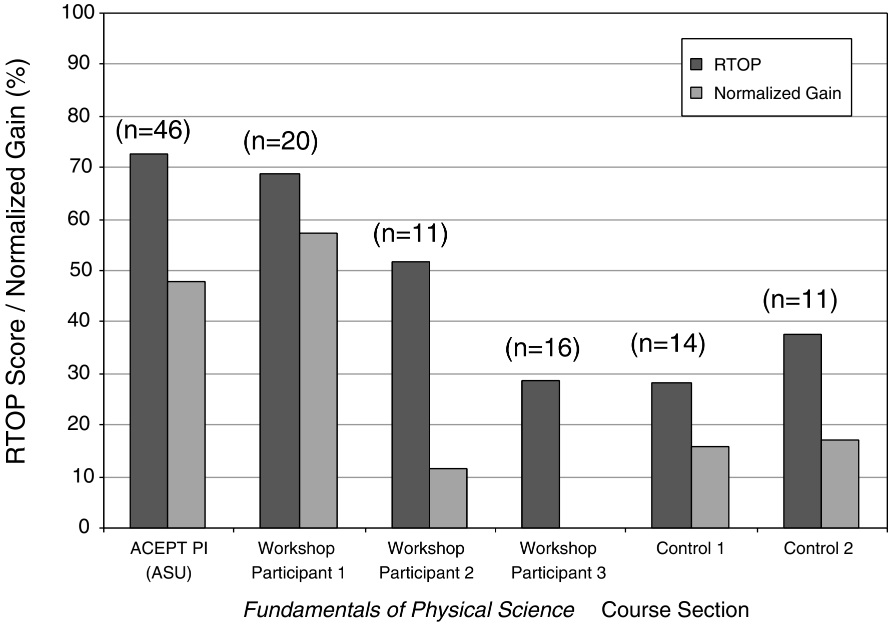

FIGURE A-1 Instructor RTOP scores and normalized gains on the test of physics concepts for ACEPT and control sections of *PHS 110*.
SOURCE: Lawson et al. (2002, p. 390). Reprinted with permission of National Science Teachers Association.

predicted because items in this section required only routine algorithmic procedures.

*The Living World (BIO 100)* is an introductory biology course enrolling about 750 students per semester. A faculty member presents three 50-minute lectures each week. Graduate teaching assistants (TAs) teach the labs. Labs meet once each week for two hours. Students must enroll for both the common lectures (all delivered by the faculty member) and one of several lab sections (each taught by one of the several TAs). TAs are introduced to reformed teaching methods during a three-day summer workshop followed by two-hour TA meetings each Friday during the fall semester.

A primary goal of *BIO 100* is to improve students' reasoning skills. Consequently, during the past several semesters, a 25-item pre- and posttest of reasoning skills has been administered (Lawson et al., 2000). Figure A-2 shows the frequency of students at each score on both the pre- and posttest and reveals substantial and statistically significant pre- to posttest gains from a recent semester (dependent $T = 14.9$, $p < 0.001$).

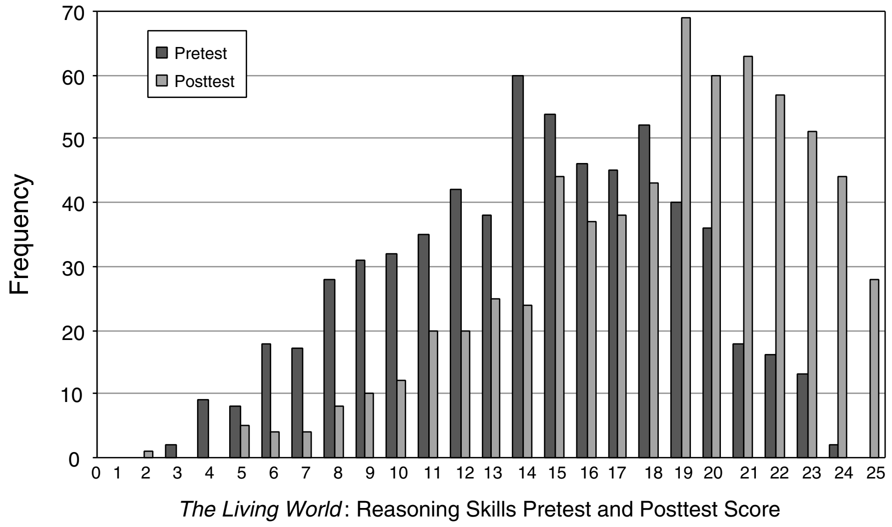

FIGURE A-2 Pre and posttest scientific reasoning scores for students enrolled in *BIO 100*.
SOURCE: Lawson et al. (2002, p. 391). Reprinted with permission of National Science Teachers Association.

During that semester, the nine TAs were independently evaluated using the RTOP. Regardless of the fact that all TAs were introduced to teaching reforms in the same manner, and all the *BIO 100* labs are inquiry (learning cycle) based, TA mean RTOP scores varied from 42 to 90 (inter-rater reliability of $r = 0.90$, $p < 0.001$). Importantly, TA mean RTOP scores correlated significantly with normalized gains in student reasoning ($r = 0.70$, $p < 0.05$).

*University Physics 1: Mechanics (PHY 121)* is an introductory course designed for physics majors that focuses on mechanics. A course evaluation was conducted using three experimental sections of *PHY 121* (i.e., sections taught by ACEPT-influenced instructors). Two experimental sections were taught at ASU and one was taught at a community college. A non-ACEPT-influenced instructor taught the control section at a community college. A diagnostic test of mechanics concepts called the Force Concept Inventory (Halloun and Hestenes, 1985) was administered to all sections to assess pre- to posttest gains. Instructors' mean RTOP scores and normalized gains were compared and a strong positive correlation was found ($r = 0.97$, $p < 0.01$). Once again, this indicates that reformed teaching methods promote student achievement.

## BOX A-3 The Nature of Science Survey

Next to each item write the number that best reflects your current belief:
1 = strongly disagree 2 = disagree 3 = don't know 4 = agree 5 = strongly agree

_____ 1. The primary goal of modern science is to describe and explain natural phenomena.
_____ 2. Hypotheses are derived from controlled observations of nature.
_____ 3. A hypothesis is an educated guess of what will be observed under certain conditions.
_____ 4. A conclusion is a statement of what was observed in an experiment.
_____ 5. Hypotheses/theories cannot be proved to be true beyond any doubt.
_____ 6. Hypotheses/theories can be disproved beyond any doubt.
_____ 7. To be scientific, hypotheses must be testable.
_____ 8. To test a hypothesis, you need a prediction.
_____ 9. A hypothesis that gains support becomes a theory.
_____10. A theory that gains support becomes a law.
_____11. Truth is attainable through repeated supporting observations.
_____12. The primary goal of modern science is to discover facts about nature.
_____13. Scientific statements that are "just a theory" are of little value.

SOURCE: Lawson et al. (2002, p. 391). Reprinted with permission of National Science Teachers Association.

*Methods of Teaching Biology (BIO 480)* is taught at ASU each spring for preservice biology teachers after they have completed, or are about to complete, an undergraduate biology major. In addition to using reformed methods to teach the preservice teachers about those reformed methods, the course attempts to help students develop their reasoning skills and improve their understanding of the nature of science (NOS). During a recent semester, students' reasoning skills (classified into developmental stages 3, 4, and 5) were assessed using the previously mentioned reasoning test (Lawson et al., 2000). Students were also pre- and posttested using a 13-item ACEPT-developed survey of the nature of science (see Box A-3). The survey includes items that focus on the meaning of terms such as hypothesis, prediction, theory, law, proof, truth, fact, and conclusion. These are terms that are not only central to the business of doing science but are also terms that are used inconsistently and sometimes even contradictorily by many, if not most,

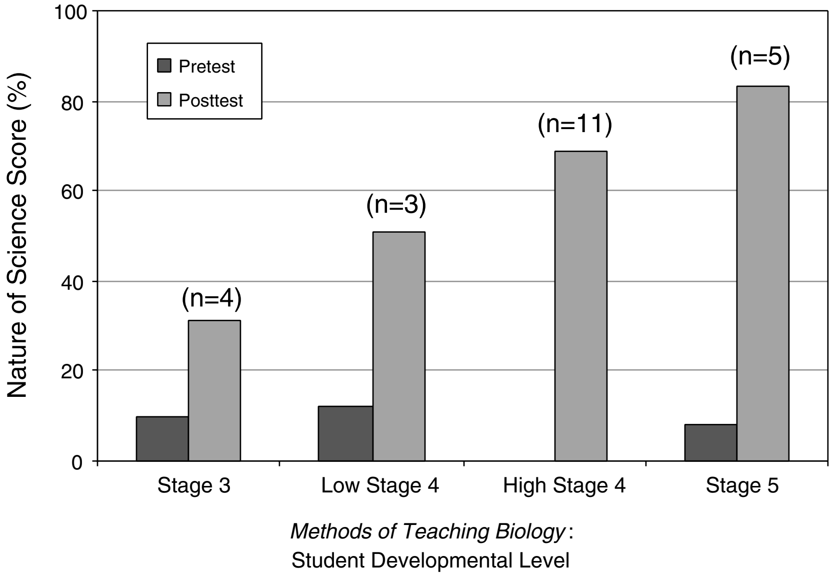

FIGURE A-3 Pretest and posttest performance on *BIO 480* students at each developmental level. SOURCE: Lawson et al. (2002, p. 392). Reprinted with permission of National Science Teachers Association.

scientists. The assumption is made that these inconsistencies and contradictions are confusing to students who are trying to better understand the research process.

As shown in Figure A-3, pretest NOS scores were low and unrelated to developmental level. However, posttest NOS scores were considerably higher. Further, posttest NOS scores were strongly related to developmental level ($F_{3,22} = 7.38$, $p < 0.01$). These results are important because they suggest that: (1) without explicit NOS instruction, biology majors learn very little about the nature of science, (2) inquiry instruction that includes explicit NOS instruction is effective at improving NOS understanding, but (3) substantial gains in NOS understanding depend, at least in part, on students' developmental level. Although current research on this last point is preliminary, a plausible prediction is that becoming a skilled inquiry teacher requires advanced reasoning skills and a good understanding of the nature of science. If this is indeed the case, then additional changes in the undergraduate curriculum will need to be made to insure that all students, particularly those who will become teachers, develop advanced reasoning skills.

## HOW EFFECTIVE ARE ACEPT-INFLUENCED BEGINNING TEACHERS?

An important component of the ACEPT evaluation has focused on the teaching effectiveness of recent graduates as they begin their public school teaching careers. A preliminary look at first-year teacher performance reveals significant differences ($p = 0.05$) in favor of ACEPT-trained teachers (i.e., mean RTOP score of 48 among 20 teachers who had enrolled in an ACEPT-influenced science or mathematics course as undergraduate students compared with a mean RTOP score of 40 among a sample [$n = 8$] of teachers who had not encountered one or more ACEPT-reformed courses during their teacher preparation program). Similar data for second- and third-year teachers were found. Importantly, the ACEPT-influenced teachers continue to outperform the non-ACEPT teachers (mean RTOP score of 62 versus 45, $p < 0.05$). Also RTOP performance improved from the first year for both groups. This improvement is encouraging because it suggests that a statewide movement to reform science and mathematics instruction (Arizona Department of Education, 1997) and complementary local reform efforts are having a positive and general impact on instructional reform.

More recently, we have found that ACEPT-influenced high school biology teachers have significantly higher RTOP scores than a group of control teachers. Further, their students demonstrated significantly higher achievement in terms of scientific reasoning, NOS understanding, and understanding of biology concepts than students of control teachers (teacher $n = 28$, student $n = 1{,}115$). Results were most divergent for scientific reasoning. Depending on the amount of ACEPT influence, reasoning skills were from 25–46 percent better among students of ACEPT-influenced teachers (Adamson et al., 2002).

## CONCLUSIONS, RECOMMENDATIONS, AND SOME FURTHER QUESTIONS

The primary result of the present evaluation is that, when implemented, the AAAS teaching principles lead to improved student achievement in a variety of undergraduate science and mathematics courses. This result not only supports the usefulness of the AAAS teaching principles, but also supports the active, learner-centered, theory upon which those principles are based. Another important aspect of the present evaluation is the development and validation of a teaching observational protocol (the RTOP). The RTOP enables trained observers to reliably evaluate instruction in terms of the extent to which it incorporates reformed teaching methods. In addition to evaluating current teaching methods, the RTOP could become an important instrument to help instructors improve their classroom instruction. Perhaps a useful extension of the present results would be a study of the sort envisioned by Feuer, Towne, and Shavelson (2002) that explores the relationship between RTOP scores and student achievement over a much larger number and diversity of courses.

The present evaluation indicates that when preservice teachers encounter reformed instruction as undergraduates they are more likely to incorporate those reforms into their own teaching practices after graduation. This result supports the familiar adage that "teachers teach as they have been taught." This is an important finding as it offers a possible solution to the well-documented need for K–12 curricular reform. Namely, reform the way in which preservice teachers learn science and mathematics as undergraduates and they will carry those reforms with them to K–12 classrooms.

Finally, the results indicate that preservice biology teachers, at least the ones in the present sample, initially know very little about the nature of science. Importantly, acquiring such knowledge appears to be linked to reasoning skill. This suggests that many science majors may not only need help in acquiring understanding of the nature of science, but they may also need help in developing scientific reasoning skills (Anderson and Mitchener, 1994; Coble and Koballa, 1996; Haney, Czerniak, and Lumpe, 1996; Lawson, 1999; Lawson et al., 2000). Clearly, much work remains to be done for college faculty to become more effective in the classroom. Perhaps the present results will contribute to that ongoing process by suggesting one way in which such improvements can be made.

Further questions include:

- Why are some faculty members resistant to reform?
- What can be done to overcome that resistance?
- What, if any, important reformed method/strategy does RTOP not measure?
- What is the best way to help faculty members become skilled teachers?
- What support system needs to be in place to encourage reform?
- What misconceptions exist regarding reform?

## ACKNOWLEDGMENTS

This material is based upon research supported by NSF under grant No. DUE 9453610. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author and do not necessarily reflect the views of the NSF. We would like to express gratitude to Terry Woodin, Harriet Taylor, and Joan Prival of the NSF, and O. Roger Anderson, chair of the ACEPT National Advisory Committee, for their continuing support and guidance.

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# Effecting Faculty Change by Starting with Effective Faculty: Characteristics of Successful STEM Education Innovators[2]

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## INTRODUCTION

For some 10 years now, I have been learning through my work as an evaluator about education faculty innovators who work in the fields of science, technology, engineering, and mathematics (STEM). As evaluators do, I moved without pause from one interesting evaluation project to the next. In fleeting moments, I have become increasingly certain that the faculty whose courses I was studying[3] share certain characteristics, but I had no opportunity to systematically consider and then articulate what these characteristics might be. So it was that upon considering Bob DeHaan's request to write about how to promote curricular and pedagogical improvements, I reasoned that findings on characteristics shared by STEM faculty who are largely successful at effecting change might help others (faculty as well as professional develop-

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[2] I shared an early draft of this document with the people listed in Box A-4, plus three social scientists who also work with STEM faculty education innovators. Many responded with comments, some of which I quote directly in this revised paper. In particular, I thank Steve Ackerman, Josefina Arce, Jean-Pierre Bayard, Aaron Brower, Ann Burgess, Diane Ebert-May, Art Ellis, Fiona Goodchild, Curt Hieggelke, Gretchen Kalonji, Elaine Seymour, Jerry Uhl, and John Wright for their insightful comments. I also thank Denice Denton and John Moore for their support for the ideas presented in this document.

[3] These faculty members were attempting to implement substantial innovations in their courses. In almost all cases the evaluations were designed to provide formative feedback to inform decisions about midcourse improvements. The findings often were also used for summative reporting purposes. All projects involved interviews with the key faculty, teaching assistants, and at least some of the students. In addition, students usually completed surveys about their learning processes. Classroom and laboratory observations were made, but on a limited basis.

ment staff and policy makers on campuses and in funding agencies) effect faculty change.[4]

How would such findings be helpful? Trained as an anthropologist, it is evident to me that people are more able to recognize who they are, and who they are not, by comparing themselves to others. And this process is more effective when the characteristics of the "others" are articulated in some detail. My hope, then, is that individuals who assess themselves and key colleagues in light of a set of characteristics shared by STEM education faculty innovators might better identify, for example, habits or implicit assumptions that may be thwarting their efforts to achieve their goals as educators.

To illustrate, a faculty member who cares deeply about teaching and learning and knows on some level that students should be more actively involved in classroom activities might realize that he differs from the innovators described here, in that he is not willing to hand over some decision-making authority to the students. Noticing this, he may then realize that he believes that students will take responsibility for their own learning but that his practice (based on teaching as he was taught) of maintaining control in the class at all times is at odds with his beliefs about student responsibility. Or, the process of reviewing this set of characteristics of successful STEM education innovators might help a faculty member realize that some of her teaching practices, while unusual in her department, are common among innovators across the country. I also reasoned that knowledge of these characteristics might enable faculty and other change agents to recognize others who have these characteristics, and who need a word of encouragement, or a new skill or contact in order to keep the faith, or, better yet, to really flourish. In other words, this kind of learning through reflection might help faculty become more accomplished and productive as reflective practitioners (Schön, 1983, 1995).

I also chose this topic for two other reasons. One is that I anticipated that two other participants in the workshop, Elaine Seymour and Robert Zemsky, would complement my focus on faculty as individuals with talks that focused on the organizational parameters that promote and constrain faculty efforts to improve how undergraduate students learn in STEM courses and programs.

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[4] Aaron Brower observed that the characteristics presented here may well also be common to faculty innovators in the social sciences and humanities. I suspect he is correct, but could not, on the basis of my experience as an evaluator, extend the generalizations presented here beyond STEM faculty.

The other reason was that I knew this paper would benefit from input from the workshop participants—many of whom I know have deep knowledge of STEM faculty innovators—about the adequacy of these characterizations and about how we might use them to inform action strategies that faculty and other change agents might use to good effect.[5]

### Methods

The group about whom I am generalizing includes essentially all the STEM faculty innovators whose innovations I have studied during the last decade, plus many others with whom I have worked and held extended discussions about teaching and learning. (I list many of these individuals in Box A-4.) Almost all of these people are successfully promoting pedagogical improvements, and some are successfully promoting curricular improvements (the latter being more difficult in that curriculum tends to be a "canon" for which an entire discipline, or at least a department, shares responsibility). Moreover, most are also effecting change among their colleagues.

The process I used to formulate these common characteristics was to conduct an informal thematic analysis based on findings that appear in evaluation reports and case studies, and on points that some of these faculty made in conversation. I organized the emergent characteristics of STEM faculty innovators into topic areas pertaining to general personality features, attitudes and habits of interpersonal interaction, learning and teaching practices, processes for changing one's own teaching practices, processes for fostering change in the teaching practices of communities, and the characteristic of "peripheral vision." In some places, I provide references to work in the emerging "learning sciences" literature that presents many of these same characteristics as key to effective learning situations, and include some of the responses of those listed in Box A-4 to these themes and to earlier drafts of this paper.

## COMMON CHARACTERISTICS OF STEM EDUCATION FACULTY INNOVATORS

### General Personality Features

Certain general personality features stand out as common to the successful STEM education faculty innovators whose work informs this paper. In

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[5] For their insightful contributions to this paper during the CUSE workshop, I thank Katayoun Chamany, Robert DeHaan, Paula Heron, Alan Kay, Priscilla Laws, Richard McCray, Lillian McDermott, Elaine Seymour, Susan Singer, Lillian Tong, Carl Wieman, Jack Wilson, Michael Zeilik, and Robert Zemsky.

### BOX A-4 Stem Faculty Innovators Who Informed This Analysis

I drew on evaluation and case studies involving the following faculty. Unless otherwise specified, these individuals are or were members of the University of Wisconsin-Madison teaching staff:

- Melinda Certain and Mike Bleicher: Wisconsin Emerging Scholars calculus
- Denice Denton: electrical engineering
- Art Ellis: materials enriched general chemistry
- Pat Farrell and colleagues, College of Engineering: introductory engineering design
- Eric Frost, San Diego State University: geology for majors
- Curt Hieggelke, Joliet Junior College: introductory physics
- Gretchen Kalonji, University of Washington: materials science
- Tim Killeen, Ben Van der Pluim, and colleagues, University of Michigan: global change
- John Moore and colleagues: introductory chemistry
- Robin Pemantle and colleagues: mathematics for preservice teachers
- Jerry Uhl and colleagues, University of Illinois at Urbana-Champagne: biocalculus; at University of Massachusetts-Dartmouth: freshman engineering
- John Wright: introductory analytic chemistry

I drew on additional information obtained during extended conversations with:

- Steve Ackerman, Center for the Integration of Research on Teaching and Learning (CIRTL):  meteorology
- Josefina Arce, University of Puerto Rico at Rio Piedras: chemistry
- Jean-Pierre Bayard, California State University–Sacramento: electrical engineering
- Ann Burgess: biology
- Judith Burstyn, CIRTL: chemistry
- Diane Ebert-May, Michigan State University: biology
- Francis Halzen, CIRTL: physics
- Jim Haynes, State University of New York College, Brockport: environmental sciences
- Michelle Hluchy, Alfred University: geology
- John Jungck, Beloit College: biology
- Jean MacGregor, The Evergreen State College: environmental studies
- Bob Mathieu, CIRTL: astronomy (principal investigator)
- Greg Moses, CIRTL: computer science for engineering students
- Jim Taylor: chemistry

SOURCE: Millar (2002, November).

short, they are risk takers and very hard workers. They make commitments and stick with them to the end. Many are inspired by a sense of mission. And they are savvy and persistent about obtaining resources, including moral and material support from proactive administrators and external funding agencies. They take pride in doing a good job for their students and often for their departments, disciplines, and/or institutions as well. Most are not especially charismatic in their personal style.

### Attitudes and Habits of Interpersonal Interaction

Many people who are not engaged in STEM education innovation can, however, be described by the general characteristics listed above. Thus, while perhaps necessary, these general features certainly are not exclusive to successful STEM education innovators. That is, they are not *defining* characteristics. By contrast, I believe that unless a person has the characteristic attitudes and habits of interpersonal interaction discussed below, they will not be in this group of successful STEM education innovators. For brevity, I list these features as follows:

- Their identity as a scholar does not depend on placing themselves above other faculty members, academic staff, graduate students or undergraduates (Wilshire, 1990). Accordingly, they listen respectfully to students ("there are no dumb questions"), strive to build on students' questions and ideas, and quickly recognize and are delighted by the occasional startling insight that a student presents. Mike Bleicher responded to this point by reminding me of the Biblical saying, "A wise man learns more from a fool than a fool learns from a wise man."
- These faculty not only are comfortable admitting to students when they did not know something or made a mistake, but also value these situations as opportunities to engage their students in the kind of problem solving that is central to the scientific process. Most of these educators are at least as interested in teaching the process by which discoveries are made as the outcomes of those discoveries. In his response to a draft of this paper, John Wright affirmed this point and illustrated how he makes good use of mistakes:

> *One of the powerful tools that I find useful in a course is to make sure that students know that making mistakes is part of the scientific process and that the key to profiting from them is making sure that you learn from them. Praising the aspects of a student's work that are good and putting the mistakes in a proper perspective can do wonders for a student's self-esteem and confidence.*

- They view students not as "outsiders" but as less experienced potential peers. Accordingly, they design their courses and interact with students with a "we're in this together" attitude. They make the effort to walk in students' shoes by taking time to recall what it was like to not have concepts and skills that they, as experts, take for granted (Leamnson, 1999). Viewing students as novice potential members of their communities, they include them in the real talk and real work of their "communities of practice" (Lave and Wenger, 1991). They therefore do not view maintaining constant control of the classroom as a virtue, but rather seek out ways to give students at least some decision-making power.
- In contrast to faculty who consider teaching a burden ("teaching load") to be accomplished in the least amount of time possible, these individuals feel genuinely excited about students and teaching.[6] They enjoy seeing their students learn, and take a certain pride in their students' accomplishments. As Josefina Arce put it, "We find pleasure in seeing our students learn—a pleasure similar to the one we feel when an experiment works well." Jean-Pierre Bayard expressed this point in a slightly different way by writing that he, for example, really cares about students, and is motivated to earn his students' respect.
- They view graduate teaching assistants as full members of the team and are eager for their input and feedback. They are willing to discuss their failures (and what they have learned from them) as well as their successes with colleagues who also are experimenting with innovation.[7]

## Learning and Teaching Practices

I turn now to learning and teaching practices that are common to the successful STEM education faculty innovators whom I know. I would venture that this set of characteristics also constitutes a basic requirement for the people I describe here, but my hunch is that, compared to the characteristics listed above pertaining to attitudes and habits of interpersonal interaction, those listed below can more easily be developed with experience.

- Successful STEM education faculty innovators experience teaching as intellectually exciting—as another opportunity to learn that is no less engaging than the scholarship they

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[6] I thank Ann Burgess and several people at the CUSE workshop for reminding me of this characteristic.

[7] Special thanks to Ann Burgess for reminding me of this characteristic.

pursue in their STEM discipline. In other words, they make learning about learning a part of their scholarship.[8] Many have explained that the challenges of teaching force them to put their research in a larger context, which often leads to new insights useful in their research. For example, John Wright finds that his best ideas—in his research as well as teaching—come from students.

- These innovators hold the conviction that good teaching demands ongoing creative effort, believe that it is important to "understand understanding" (Wiggins and McTighe, 1998), and take the time to learn about teaching. As one member of the CUSE workshop put it, they recognize that "self-reeducation takes years." These individuals eschew recipes or quick fixes, and believe that everything one tries—whether successful or not—enhances their capacity to do better the next time (Stevens, 1988).
- They understand that learning depends on feeling puzzled, perturbed, and curious, and on tolerating ambiguity. They value cognitive dissonance as a precursor to the process of changing a person's understanding (Jonassen and Land, 2000). Thus, in their own practice (as educators and researchers), they are quick to question the status quo and their own beliefs when they notice an inconsistency.
- They have very high expectations of students. They want them to go beyond "knowing that" to "knowing how" (Brown and Duguid, 2000) and "knowing why" (Hieggelke, personal communication). For that matter, they want students to get so engaged with their learning that "they try on for size" the identity of scientist, mathematician, or engineer (Seymour et al., 2002).
- They hold the conviction that if faculty will demand it, students will accept the challenge of becoming independent thinkers. Accordingly, they expect their students to push themselves to comprehend and use difficult ideas and acquire new skills. Persuaded that attempts to think for students or to control their thinking may actually interfere with their learning, they seek to provide course materials and an environment that pushes the students to do the thinking and, as Jerry Uhl put it, to "learn to learn." As Ann Burgess commented, "Students learn more when you figure it out together than when you just tell them the answer!" Accordingly, they know that they and any other (graduate or undergraduate) course instructors must eschew the role of authoritative provider of answers and instead play the role of a guide—some-

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[8] I thank Priscilla Laws and Lillian McDermott for emphasizing this point.

one who has traveled these paths and remembers how it was the first time.[9]

- They believe that learning entails a constant moving back and forth between "practice" (trying things out, making things happen) and "beliefs" (theories about the nature of things and why things happen) (Lave and Wenger, 1991; Wertsch, 1993). Thus, they design their courses to provide students with "practice" by using hands-on problems and challenges. (Some of them refer to this approach as "learning on demand.") They design their courses to provide learning processes that engage students in reflection through genuine dialogue with senior peers (e.g., fast and context-sensitive feedback from teachers and expert practitioners), other students (e.g., problem-solving in groups), and self-reflection (e.g., individual writing and problem solving).
- They believe that they should only ask students to learn things that there is good reason to believe will "matter" to the students. Thus, while fully expecting them to eventually master difficult and abstract concepts, they use "real stuff" in the curriculum, that is, open-ended problems, hard problems that they can relate to their everyday lives. They resist including material that not only the students will never use, but the faculty themselves would never use.[10]

Aligned with their efforts to engage students in genuine dialogue is their tendency to use assessment not to grade/judge (a process that closes opportunities to learn), but rather to figure out what their students are assuming and concerned about (a process that opens up opportunities to learn). They consciously use these "formative" assessment practices to help keep themselves aware that most of their students do not possess the mental models and habits that they had when they were students, let alone now that they are experts in their discipline. Evaluation findings on courses taught with this approach revealed that for many of the students in their classes, the learning, not the grade, was paramount (see, for example, Courter and Millar, 1995; Millar, Alexander, and Lewis, 1995; and Wright et al., 1998).

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[9] Several of the CUSE workshop participants pointed out that, in fact, most successful scientists approach the undergraduate and graduate students who work in their labs or on their projects in this way. We agreed, however, that STEM education innovators are distinguished from other scientists in that they believe that not just "their own," but the vast majority of the students in their undergraduate lectures and laboratories will rise to these challenges.

[10] Special thanks to Steve Ackerman for this point.

### Processes for Changing Their Own Teaching Practices

The STEM education faculty innovators with whom I have worked or with whom I have discussed teaching at length are similar in the ways they go about changing their own teaching practices.

- They are proactive and very pragmatic problem solvers. By this I mean, borrowing a concept from Covey (1990), that they work in their "circle of influence," and while aware of problems in their "circle of concern," they spend little if any time or emotional energy on these concerns (pp. 82–83).[11] Related to this point, they tend to be people who do not waste time casting blame (on the students, K–12 teachers or the K–12 system, or the system in place at their college or university) when they realize there are problems. Instead, they focus their energies on the business of doing what they can to address these problems.
- They take an experimental—that is, an intentional, systematic, and sustained—approach to solving their problems with teaching and learning. In particular, they transform their concerns into actionable "problems," develop plans and strategies that they hypothesize will solve their problems, and have in mind from the beginning what outcomes they will accept as sufficient evidence of success. They constantly seek and reflectively use feedback information. That is, they gather information on how well their strategies work, analyze and reflect on this feedback—often mulling it over with colleagues (Lave and Wenger, 1991)—and adjust their strategies accordingly.
- They use this act-feedback-reflect-adjust and act cycle on an ongoing and cumulative basis, working step-by-step and bringing their entire store of past feedback information to bear on each new adjustment (Stevens, 1988). I illustrate and improve on this point by quoting Steve Ackerman's response upon reading it in an earlier draft:

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[11] With regard to this point, Diane Ebert-May noted that successful senior innovators nonetheless devote substantial time to helping younger scholars learn how to redirect their energies from their sphere of concern into their sphere of influence.

*I relate this point to my own experiences in teaching an introductory weather and climate course. I began by seeking no feedback from peers. A couple of years into teaching it, I realized the need for and value of this, and for a few years I sought out lots of peer review. Now, after about ten years, I don't solicit peer feedback. Rather I get it from the teaching assistants and students. So I wonder, am I getting lazy, or overconfident, or am I fooling myself that student feedback is the most appropriate for this stage in my career? Or does the cycle you mention include different groups?*

- They purposely engage with peer learning communities (2–10 people) and/or networks (up to 100) of people who are interacting about shared problems and pursuing similar action strategies (Hutchings, 1996; Shulman, 1993). That is, they develop new ideas and insights, and obtain new information, about teaching by interacting with "near peers" (Rogers, 1995) in local communities and in professional societies, or at least the education branches of those societies. In a few cases these peer groups are department based. Most often they are cross-departmental or cross-institutional. The latter usually are or were externally funded by a foundation (predominately the National Science Foundation, often the Howard Hughes Medical Institute, among others). In some cases, these cross-institutional networks consist of faculty who worked with the same professor or research groups as graduate students.[12] I saw no case in which the group consisted of a faculty developer and an individual STEM faculty member.
- Last, I would list an *eventual* turn to the larger community of educators as a characteristic that these STEM faculty share with regard to how they go about making change in their own courses. Once they are quite certain that they have accomplished something valuable as innovative teachers, most of them begin to notice that there is a body of research on learning, and that there is a big network of people in diverse disciplines who are involved in this business. At this point, they begin to participate in larger networks through meetings, email, and listservs, sharing citations and reading certain key pieces that make the rounds in their disciplinary communities (Shulman, 1993). In response to this point, Steve Ackerman wrote, "I would add that the large networks, in turn, play a role in seeking out the innovators." And Diane Ebert-

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[12] Special thanks to Alan Kay for this point.

May's response to this same point beautifully illustrates Steve's addition:

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> *I think more and more faculty are becoming aware of this network and body of research before or while they are embarking on their pathway of change. There are multiple points along the continuum for people to begin, and they don't necessarily wait until they have accomplished something valuable. Often, it depends on who they meet or hear from initially. For example, for [her current STEM education improvement project], one team traveled by car 12 hours to a field station. Two of the three were going only because their friend asked them to. Their arms were crossed in front of their chests all the way, teeth clenched, and attitude, well, not good. After five days there, they were ready to rock and roll, and have continued doing so ever since.*

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## Processes for Fostering Change in the Teaching Practices of Communities

Essentially all of the STEM education faculty innovators about whom I generalize here are taking leadership roles in order to foster change in their departments, specific disciplines, and/or in STEM education overall. They are similar not only in their willingness to play these roles, but also with respect to their basic reason for doing so: they are committed to helping others benefit from the innovations in teaching and learning about which they have learned. Whether operating at very local or national levels, each of these leaders has left the lab and the classroom for at least some of their time in order to marshal and then manage the resources that leaders need to be successful. Each is guided by homegrown models of change (such as the "dipping the toe" model that guided Art Ellis for many years) that they may or may not have articulated explicitly.[13] Each knows the importance of building networks with other innovator colleagues and with campus administrators, and many are very skilled at building communities focused on finding ways to make change. They know that unless they collaborate and build on one another's efforts, it is not likely that their innovations will become the new status quo, that is, be institutionalized.[14]

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[13] For a useful discussion of the theories of change held by STEM education faculty innovators, see Seymour (2002a).

[14] Special thanks to Lillian McDermott and Priscilla Laws for their insights about these points.

With the help of participants at the CUSE workshop, I realized that these innovator-leaders might be organized into different groups, depending on their motivation:

- Some of these leaders' primary motivation is to support and encourage other science education innovators, many of whom feel, and indeed are, marginalized and are vulnerable. Among these leaders are some who find that while their efforts are not appreciated in their own departments, this price is worth paying because of the influence they have on colleagues elsewhere across the nation. To be sure, well-known researchers, such as Eric Mazur (physics, Harvard University) and John Wright (chemistry, University of Wisconsin-Madison), are more likely to have this type of national influence, due to their visibility within their disciplines.
- Others are primarily motivated to help their colleagues by developing reliable new knowledge about how students in their discipline learn, and by providing tested innovative curriculum resources that can make others' efforts to adapt these new methods much easier. Faculty at all types of institutions are taking this leadership path with noted success. Examples include John Jungck (biology, Beloit College), Lillian McDermott (physics, University of Washington), Curt Hieggelke (physical sciences, Joliet Junior College), Deborah Allen (biology, University of Delaware), and Dave Gosser (chemistry, City College of New York).
- Some are primarily motivated by the belief that improving the way we teach science is an excellent way to improve conditions in the world at large. Gretchen Kalonji (materials science, University of Washington) exemplifies individuals with this motivation. As she explained, in response to a draft of this paper:

> *If we believe that education is indeed a path for democratizing society, for providing economic opportunity for our youth, etc., and if we know that we are doing a poor job at it, and/or living with methodologies that are exclusionary, it is a moral issue. I know that many of the colleagues I admire the most share these motivations at the core.*

- Yet other innovator-leaders believe they can most effectively help others by influencing policy at the national level. People in these positions generally need excellent reputations as researchers and administrators, in addition to their credentials as education innovators. Examples of these leaders include Judith Ramaley (assistant director, Education and Human Resources Directorate, National Science Foundation), and Robert DeHaan (director of the Committee on Undergraduate Science Education, Center for Education, National Research Council).

- Last, there is a group of STEM education innovator-leaders who, as members of the National Academy of Sciences or as Nobel Laureates, wield enormous influence because their credibility as researchers and leaders within their disciplines and departments is beyond question. In this group are, for example, in mathematics—Hyman Bass (University of Michigan) and Richard Tapia (Rice University); in physics—Leon Lederman (University of Chicago) and Carl Wieman (University of Colorado, Boulder); in astronomy—Richard McCray (University of Colorado, Boulder); in chemistry—Bradley Moore (Ohio State University); and in biology—Bruce Alberts (president, the National Academy of Sciences).

### A "Positional" Characteristic—Peripheral Vision

Before concluding, I add a characteristic about which Elaine Seymour reminded me. Upon reading a draft of this document, she wrote:

> *As a sociologist (I suppose), I notice that the innovators, which I also see as participating in the loose, cross-institutional national networks that you reference, often comprise people who are in some ways marginal in their relationships to their departments. I note that women are especially overrepresented, given their smaller numbers in most science disciplines except biology. There is also an important group of "radical seniors" whose invulnerability as distinguished researchers gives them protection, high visibility, and a role as spokespersons. There are also more people with less traditional career paths—including some who have walked away from the university tenure process into community and liberal arts colleges, and into research and educational scholarship roles.*[15] *In this group of people there are also more young faculty (despite the tenure risk), and perhaps more scholars of color.*
>
> *My theory is that people who stand slightly off-center "see" the need for change in ways that people who are trying to compete with each other for mainstream recognition by traditional means can't always see, or (perhaps more importantly) can't afford to see.*

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[15] Parker Palmer makes this point at some length in his piece on "a movement approach to educational reform" (1992).

I have noted this same characteristic repeatedly, and especially when listening to these educators (those in Box A-4 and many others) respond to my request that they recount why and how they got so involved in this education reform business. Each told a story of being, or at least observing the traditional classroom as, an "outsider." Of note, almost to a person, when telling their stories, these individuals appeared to enjoy their "off-center" position, even though in some cases it placed them at some risk.

Upon reflection, I am coming to believe that just as their ability to discover patterns in the unfamiliar is a key to these faculty members' success as scientists, a key to their success as education innovators is their ability to discover patterns in the all-too-familiar world of traditional classrooms and other higher education settings. This ability to see the familiar anew depends on the capacity to see, as Bateson (1994) puts it, with "peripheral vision," to notice out of the corner of the eye something important about what is in front of you. It entails taking what anthropologists call the "participant observer" stance toward situations in our everyday world, and not taking these situations for granted. Standing outside the taken-for-granted mainstream, a person is better able to see things in a new light, to perceive the need for and possibilities for change, and then return to the mainstream to work on accomplishing those changes.

The capacity to use peripheral vision depends in part on one's choice to do so. However, as Seymour suggested, people who are different, for some reason or other, are more likely to take this participant observer stance. Pursuing this point, Lillian McDermott noted that using peripheral vision is a great source of intellectual excitement, a fascinating way to learn—and in particular, an excellent way to learn about teaching.

## DISCUSSION AND CONCLUSIONS

This set of characteristics shared by STEM faculty who are largely successful at effecting change (at least in their own courses) begs the question of how these people fare within their departments and institutions. As noted above, they are wise enough to work in their sphere of influence and avoid wasting their energies on things that they cannot affect. To be sure, there are cases where these "things they cannot affect" affect *them* altogether too much, as when assistant professors are denied tenure because their departments did not recognize or sufficiently value their accomplishments in the scholarship of teaching. But, as a growing body of evaluation and research findings indicate, there are many other cases where one can see that these innovators have become leaders whose spheres of influence have grown into and positively transformed features of their departments and institutions.

I venture that the extent to which STEM education innovators thrive and achieve their goals as educators depends not only on how well they manage those "things they can affect," but also on the constraints posed, and opportunities afforded, by the institutional and cultural circumstances in which they are embedded. Several of the innovators who responded to the initial draft of this paper wanted to pursue questions about what circumstances pose constraints that are too risky and for whom and, more generally, about what lessons we can learn from innovators who successfully maneuver around the constraints and play into the opportunities. I do not attempt to address those questions here.

However, in their presentations at the CUSE workshop, Robert Zemsky and Elaine Seymour highlighted some of the constraints that innovators face. For example, Zemsky (2002) called our attention to the enduring resistance to change that is characteristic of universities, while Seymour (2002b) brought to light the daunting power of a cultural system, supported by myriad organizational practices, in which faculty and students tacitly agree to dispense with the formal educational tasks required of them by following paths of least resistance. They also pointed out a number of key opportunities that current circumstances afford STEM education innovators, such as market pressures for more effective and efficient learning that are experienced by, for example, medical and business schools (Zemsky); and a climate of trust among faculty, graduate students, and undergraduates in STEM classrooms (Seymour).

I would ask you to consider yet another factor—one that can just as powerfully "afford" as it can "constrain" the kind of change sought by these faculty innovators. This factor is the faculty themselves. Here is my argument. If universities are enduring institutions, it is not because they resist, but rather because they selectively embrace, change—following the best lessons learned and principles held by their typically "ungovernable" faculty. Innovation in STEM education is underway in the myriad decisions made and actions taken by ungovernable faculty who are learning from their students and one another, and who are encouraging one another in loose, cross-national, and inexorably expanding networks comprised of people like those featured here.

Moreover, it is important to note that

the successful STEM education innovators featured here include a number of our "radicalized seniors."[16] These people are important because faculty, however ungovernable, are inclined to learn from respected peers and to notice the values and actions of the most esteemed and altogether credible members of their disciplines.

In conclusion, I venture that, as STEM faculty innovators—"radicalized seniors" and many, many others—expand their spheres of influence, they are reshaping and redefining what it is that "the faculty" takes as acceptable norms for teaching STEM courses. And (coming full circle), to the degree that this paper helps restructure how we perceive these innovators among us, helps make them visible in new ways, it participates in this process of reshaping what we take for granted in STEM education.

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[16] At Zemsky's suggestion, I have added a suffix to Seymour's term ("radical seniors") to indicate that these people either actually became more radical, or allowed themselves to develop and act on their peripheral vision, once they became "seniors."

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# On Encouraging Faculty to Pursue Instructional Reform

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When challenged to defend the staying power of their institutions, university presidents often invoke Clark Kerr's (1987) observation:

> About 85 institutions in the Western world established by 1520 still exist in recognisable forms, with similar functions and with unbroken histories, including the Catholic church, the Parliaments of the Isle of Man, of Iceland, and of Great Britain, several Swiss cantons, the Bank of Siena and 70 universities. Kings that rule, feudal lords with vassals, and guilds with monopolies are all gone. These 70 universities, however, are still in the same locations with some of the same buildings, with professors and students doing much the same things, and with governance carried on much the same ways (p. 184).

Kerr was testifying to the enduring nature of the university—its ability to survive when challenged, to adopt when necessary. For defenders of the faith, nothing more is needed; however, for the naysayers among us, the image suggests something more than Kerr intended. What many see as enduring resilience, others perceive to be the academy's early resistance to alteration and later its resistance to change.

## DEFINING THE CHALLENGE

Kerr's observation also suggests the near impossibility of the assignment I have accepted: to explore "some of the options that university administrators—presidents, deans, department chairs—have at their disposal to encourage and support their faculty in instructional reform." What Kerr and his appeal to the historic university make clear is that change in the academy is slow, probably imperceptible, and not likely to be the result of the strategies of individual presidents, deans, or department chairs.

For purposes of discussion, let me suggest three propositions that lend a practical perspective to this traditional tension between resilience and resistance. The first is simply that most universities—and almost all research universities—are presided over by faculty guilds. Membership is for life. Independence and autonomy are guaranteed, as long as the guild members respect the privileges and honor the obligations that membership confers, including the obligation not to meddle too deeply in the practices of one another. We teach largely as we were taught. When we experiment with new modes of instruction, we tend to do so quietly, not wanting to draw too much attention to ourselves. We tend to work alone, largely eschewing group projects. As in most guilds, acceptable practice is what everybody does—a kind of implicit regression to the mean—so that changes in curricula and instructional format require broad agreement that something, in fact, is broken and requires fixing.

My second proposition concerns the nature of the offices that presidents, deans, and department chairs occupy. We know they are administrators; we can hope they are—or eventually become—leaders. What we cannot expect them to be, however, are managers. They seldom command significant resources. Most of their funds, regardless of the size of their budgets, are spent before they can make a single decision or investment. Beyond their immediate staffs, they, like the pope, command no troops. Even the very words that frame this session reflect the problems nearly every president, dean, and department chair face: they cannot enforce change but merely explore "options…to encourage and support their faculty in instructional reform."

At the University of Pennsylvania, Nichole Rowles is completing a dissertation (2003) that will update Cohen and March's application of the *garbage can model* (Cohen, March, and Olsen, 1972) to describe decision making in the modern university. Rowles is documenting the extent to which presidents and their staffs, in particular, are attempting to adapt corporate models of decision making while their faculties cleave to the older, more established norms representative of guilds and garbage cans. The most striking differences involve the roles of strategy and data. In the corporate model, a strategy is what sport enthusiasts will recognize as a game plan: an envisioning of the job at hand, an enumeration of the resources available to achieve the desired goal, and a focusing on the tactics necessary to make one's strategy operational. In all three modes, data play a critical role in defining possibilities, calculating risks, and measuring results. On the other hand, most faculty think in different terms—not of strategies, but of strategic plans that, for the most part, are lists of things other people should be doing.

What is most striking, however, is the relative absence of calls for data from the faculty's perspective. They enforce no culture of evidence for institutional decision making, despite the fact that most scholars spend their lives in pursuit of data and empirical observation. Instead, there are experiences and lessons learned—and, above all, principles derived from firmly held beliefs. In one institution in Rowles' study, the faculty came to believe that athletes were being given preferential treatment and were being credited with higher grade point averages (GPAs) than they deserved. Despite the presence of a study conducted by that university's office of institutional research, which documented that athletes' GPAs were not being inflated by the suspect practice, the faculty overwhelmingly voted to outlaw the practice. When Rowles asked the head of the faculty senate why they had ignored the study, he responded simply, "You have to understand, it was not a matter of data but of principle."

Hence, the problem faced by presidents, deans, and department chairs. Curricular reform, like all academic decisions, becomes more a matter of principle than of strategy—a matter of what is intrinsically right as broadly understood by those vested with responsibility for determining what is to be taught and how. It is a perspective that is too easily caricatured, as when members of the faculty are quoted as saying, "It's not a matter of what students want but what they need." As faculty, we have spent our lives learning what students need; we are collectively responsible for the knowledge base they must master, as well as exemplars of the role free and unfettered inquiry needs to play within every educational institution. When a president or dean speaks of the need to update the curriculum, incorporate more technology in the classroom, or recruit different kinds of teachers, the faculty not surprisingly ask: "Why? Who says what we must do?" And if the president or dean says, "Because we need to pay attention to the market in order to enroll the kinds of students we want to teach," the natural response is: "But markets do not know what we know."

Actually there is a better rejoinder which faculty are not likely to deliver, largely because, as a matter of principle, they seldom pay attention to the workings of the market for undergraduate education. What those of us who study those markets know is that there is no market for good teaching—and that is my third proposition. There is precious little evidence that students choose where they enroll based on how faculty teach. Alverno College has learned that lesson all too well. Universally acclaimed for its pioneering curriculum and innovative ways of teaching, Alverno remains an institution that has proven far more successful at attracting academic visitors and foundation grants than students. Not surprisingly, the *U.S. News and World Report* rankings hardly bother to talk about teaching or curricula, choosing instead to focus on resources and reputations. Most presidents and deans know that the building of their institutions—and not so incidentally the building of their personal portfolios—depends fundamentally on increasing revenue and building reputations, neither of which rest on instructional reform.

## MAKING THE CASE

Having defined the challenge, let me hasten to add that achieving instructional reform is not impossible, just very difficult. To understand what it might take to overcome the inertia of the guild, on the one hand, and the disinterest of the market in good teaching on the other, I want to focus on a few examples of success. They suggest the necessary conditions that an innovative president, dean, or department chair might exploit in pursuit of instructional reform.

The first is medical education leading to the M.D. Schools of medicine were among the first to experiment with and then broadly adopt self-paced and computer-assisted instruction. They have adapted a host of strategies to cope with an exploding knowledge base that can no longer be mastered, in the sense that basic anatomy can be mastered. And they have welcomed—some would say shamelessly embraced—nonphysician and non-Ph.D. instructors.

Why has medical education been able to achieve what most reformers of undergraduate education have only flirted with? There are several answers. In the first place, medical educators teach very smart, highly disciplined students for whom efficient learning is of enormous benefit. If self-paced, computer-assisted instruction promises that one can learn more and faster, then earnest students will believe it is worth a try. It is also the case that, in medical schools, teaching loads do not determine the size of the faculty group. In undergraduate education, learning efficiency all too often means the need for fewer faculty slots. And not to be overlooked is the fact that most medical schools have had and continue to have ample resources with which to experiment with new instructional technologies. Finally, there is a measurable premium attached to good or at least successful teaching: better performance on board exams and better placements for the class as a whole in the competition for residencies. Outcome measures spur reform, particularly when those both within and beyond the academy sense the value and appropriateness of the measures themselves.

My second example derives from the growth of executive education programs at most of the nation's leading business schools and their subsequent impact on the general business curriculum at both the graduate and undergraduate levels. In the early 1990s, when most of these programs were being launched, I asked the dean of one business school to account for the popularity of this particular form of education. Poised to build a hotel for his own new executive education program, he gave an answer that has stuck with me ever since.

The trend began as a kind of copycat phenomena, after Northwestern's Kellogg School and then Penn's Wharton School had launched their big, expensive initiatives. Soon, more and more schools followed suit; as they began to attract seasoned executives and managers to their "exec-ed" classrooms, the deans and faculty of these schools made a crucial discovery. Enrolled executives and managers began telling them that their traditional bread-and-butter business programs were in danger of precipitating out of the market. As one executive was reported to have said, in the past we did not so much care what you taught your undergraduates and M.B.A. students. What we expected from you was screening and certification, and figured that what happened in the classroom could do no harm. Now we are not so sure. Maybe what you are teaching really is standing in the way of the kinds of companies we are trying to build. The result across this set of select business schools was a rush to introduce educational experimentation and reform—a development that eventually came to energize business faculty across a wide spectrum of schools.

My last three examples are drawn from the world of undergraduate science and math instruction. In the 1980s, Bill Massy and I conducted a study of how departments make decisions about who teaches what (Zemsky, Massy, and Oedel, 1993). It was fundamentally an interview study, in which Bill and I spent upwards of an hour with every chair from a department that taught undergraduates at ten selective colleges and universities. What struck us was the degree to which physics departments seemed to be different; their chairs evidenced a passion for teaching and a willingness to be judged by the quality of both their curricula and their teaching efforts.

Several years later I came across Jack Wilson's experiments with Studio Physics (http://www.rpi.edu/dept/phys/education.html) at Rensselaer Polytechnic Institute (RPI) and was again reminded of the unique commitment to teaching evidenced across this discipline. What helped to make Studio Physics work at RPI was the presence of an established means of verifying the quality of this alternate form of instruction. All of the roughly 900 freshmen each year who take the basic introductory physics course sit for the same set of examinations, regardless of the section to which they were assigned. Studio Physics was able to win adherents because it could prove not only that it was more efficient in terms of the resources it consumed, but also that it produced as good or better results than teaching physics the old-fashioned way.

Collegiate mathematics instruction provides the same pair of lessons: that a disciplinary commitment is required, paired with a way to ensure the discipline that alternate ways of teaching produce measurable improvement. In the 1980s, the mathematician I knew best was Mort Lowengrub, then dean of arts and sciences at Indiana University. I asked him one night over dinner what accounted for his discipline's interest in improving mathematics instruction. His answer, as I best remember, went something like this: "We are an endangered species, and we know it. We are not educating enough young people to sustain ourselves. We are in a downward spiral: fewer young people interested in mathematics translates into less demand for mathematics instruction, which then increases the probability that among the next student cohort there will be even less interest in mathematics—and so the cycle repeats itself. To break the cycle we need to be in the business of actively seeking converts."

My last example derives from the experiences of undergraduate geology programs, particularly those offered at liberal arts colleges, over the last three decades. The oil and related energy crises of the 1970s resulted in a boom in geology majors, which in turn resulted in rapid increases in the sizes of geology departments. By the 1990s, however, the boom had gone bust, and the departments that had enjoyed rapid expansion suddenly found themselves teaching fewer students and warding off aggressive deans who wanted to shift their faculty billets elsewhere. At the time, I was engaged in a major study of the coherence of the collegiate curriculum, which examined the transcripts of graduates from more than 200 colleges and universities. Overall, we found what most observers expected: there was little coherence, little course sequencing, little sense of an ordered progression through an established body of knowledge. The principal exceptions were the sciences, primarily physics, chemistry, and engineering.

Using the computer printouts of the statistical models that produced these results, the research team developed an elaborate parlor game in which we would look at the structure of courses and prerequisites and then try to guess the department and kind of institution to which the particular printout belonged. Although the output had been stripped of all departmental identifiers, we became very good at noticing the subtle differences among disciplines and between institutional type. But one profile stumped us nearly every time: those of departments of geology at liberal arts colleges, which for the most part we mistook for departments of English. When we followed up the statistical analysis with a set of interviews, I gingerly asked the first geology chair I encountered if he was surprised that the structure of his curriculum was indistinguishable from that of the English department. He replied, “Not at all. Actually we face the same challenge of convincing undergraduates that what we know and teach is intrinsically interesting—that it can be fun!” (Zemsky, 1989).

## LESSONS

There are four basic lessons I would extract from these stories and observations, as a means of promoting the kind of discussion we need to have:

1. The first is that the guild itself must feel threatened before it is ready to change. No amount of talking or trying to explain that instructional reform is “good for you” is likely to substitute for the cumulative experience of witnessing the marginalization of what you consider to be important.
2. Curricular and instructional change, when it comes, is more likely to extend from the top of the institutional hierarchy down rather than bubble up from the bottom. What makes change so unlikely is the fact that it must come from those most advantaged by current arrangements and practices.
3. Curricular and instructional change is easier to promote when the students to be taught differently are not only smart and disciplined but also have a vested interest in the outcomes of the experiment.
4. Curricular change is inherently expensive, since the old ways of teaching will not be abandoned until the new means have fully demonstrated their staying power.

And, finally, some advice:

- To deans, in particular, don't tilt at windmills—rhetoric is nice, but the frustration of unfulfilled promises in the end overwhelms.
- While it sounds good, the recruitment of star teachers is likely to have little impact.
- Changing the tenure rules only serves as a long-term strategy when the goal is curricular and instructional reform.
- Pick your targets, spend your money.
- Invest in strong programs.
- Experiment with breaking the rules—particularly those governing the time and mode of delivery.
- Look for external markets to develop and then harvest those which provide visibility plus funds for experimentation.  Three markets  are readily available:

* The teaching of science in primary and secondary schools.

* Making corporate groups scientifically literate.

* Building a public policy understanding of science.

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# Appendix
# B

# Reference Paper

# Improving Student Learning in Science Through Discipline-Based Education Research

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## INTRODUCTION

I would like to thank the Council of Scientific Society Presidents for the 2000 Award for Achievement in Educational Research. The accomplishments recognized by this honor are the result of many contributions by faculty, postdocs, graduate students, K–12 teachers, and undergraduates in the Physics Education Group at the University of Washington.

Perhaps my "most seminal research achievement" has been to demonstrate, in the context of physics, the value of discipline-based education research. This type of research differs from traditional education research in that the emphasis is not on educational theory or methodology in the general sense but rather on student understanding of science content. For both intellectual and practical reasons, discipline-based education research must be conducted by science faculty within science departments. I shall present some evidence that this is an effective approach for improving student learning (K–20). The emphasis here will be on introductory university students and K–12 teachers.

## CONTEXT FOR RESEARCH

A brief description of the Physics Education Group can set a context for our research. Our group is an entity within the Physics Department in the same sense that there are groups in other subfields of physics. The courses in the department provide the primary environment for our investigations. Most of our work involves two populations: undergraduates in the introductory calculus-based course and prospective and practicing K–12 teachers who are taking special courses designed to prepare them to teach physics and physical science by inquiry. Our investigations also include students in engineering and in advanced undergraduate and graduate physics courses.

As part of our research on how to improve student learning in physics, we try to identify specific difficulties that students encounter in the study of various topics. The results are used to design instructional materials that target these difficulties and help guide students through the reasoning required to overcome them and to develop a coherent conceptual framework. Assessment of effectiveness with students is an integral part of the iterative process through which the Physics Education Group develops curriculum. To ensure applicability beyond our own university, our materials are also tested at pilot sites (e.g., Georgetown, Harvard, Illinois, Maryland, Purdue).

Our two major curriculum projects are *Physics by Inquiry* (McDermott, Shaffer, and Rosenquist, 1996) and *Tutorials in Introductory Physics* (McDermott, Shaffer, and the Physics Education Group, 1998). The development of both is guided by research. The first is a self-contained, laboratory-based curriculum for the preparation of K–12 teachers; the second is a supplementary curriculum that can be used in conjunction with any standard text.

## PERSPECTIVE ON TEACHING AS A SCIENCE

The perspective that teaching is a science, as well as an art, motivates our work. Considered as a science, teaching is an appropriate field for scholarly inquiry by scientists. This view is in marked contrast to that held by many science faculty.

A more traditional view was expressed in 1933 in the first article in the first journal published by the American Association of Physics Teachers (AAPT). In “Physics is Physics,” F.K. Richtmyer (Cornell University) argued that teaching is an art and not a science. He quoted R.A. Millikan (California Institute of Technology) in characterizing science as comprising “a body of factual knowledge accepted as correct by all workers in the field.” Richtmyer went on to say: “Without a reasonable foundation of accepted fact, no subject can lay claim to the appellation ‘science.’ If this definition of a science be accepted—and it seems to me very sound—then I believe that one must admit that in no sense can teaching be considered a science.”

Although this is a somewhat limited definition of science, I would like to challenge the implication that it is not possible to build “a reasonable foundation of accepted fact” for the teaching of physics (and, by extension, other sciences). For example, we have found that most people encounter many of the same conceptual and reasoning difficulties in learning a given body of material. These difficulties can be identified, analyzed, and effectively addressed through an iterative process of research, curriculum development, and instruction. Both the learning difficulties of students and effective means for addressing them are often generalizable beyond a particular course, instructor, or institution.

If one documents intellectual outcomes for student learning, teaching can be treated as a science. If the criteria for success are clearly stated and the results are reproducible, findings from research can contribute to "a reasonable foundation of accepted fact." This foundation is represented by a rapidly growing research base.

The personal qualities and style of an instructor contribute to the aspect of teaching that can be viewed as an art (a benefit confined to the instructor's class). However, when student learning is used as the criterion (as distinct from student enthusiasm), we have found that effective teaching is not as tightly linked as is often assumed either to self-assessment of learning by students or to their evaluation of the course or instructor.

## FOCUS ON THE STUDENT AS A LEARNER

The focus of our research is on the student as a learner, rather than on the instructor as a teacher. We try to determine the intellectual state of the student throughout the process of instruction. To the degree possible, we try to follow the procedures and rules of evidence of an experimental science. We conduct our investigations in a systematic manner and record our procedures so that they can be replicated. We use two general methods: individual demonstration interviews (which allow deep probing into the nature of student difficulties) and written tests (which provide information on prevalence). Continuous pre-testing and post-testing enable us to judge the effectiveness of instruction.

Although experienced instructors know there is a gap between what they say and what students learn, most do not recognize how large the gap can be. The usual means of evaluation in physics courses—the ability to solve standard quantitative problems—is not adequate as a criterion for a functional understanding and unfortunately reinforces the perception of physics as a collection of facts and formulas. Success on numerical problems does not provide adequate feedback for improving instruction. Questions that require qualitative reasoning and verbal explanations are essential.

Our investigations have shown that on certain types of qualitative questions, student performance in physics is essentially the same: before and after standard instruction by lecture and textbook, in algebra-based and calculus-based courses, whether or not there is a standard laboratory, whether or not demonstrations are used, whether classes are large or small, and regardless of the proficiency of the instructor as a lecturer. The situation has been the same in introductory mechanics, electricity, magnetism, waves, optics, and thermodynamics. We have also found that advanced students often have difficulty with qualitative questions on introductory physics, as well as on topics such as special relativity and quantum mechanics.

There is by now ample evidence that teaching by telling is ineffective for most students. They must be intellectually active to develop a functional understanding. The instructor of a course determines the emphasis, motivates students, and can promote a view of science as a human endeavor. However, he or she cannot do the thinking for the students. They must do it for themselves. Some are reluctant to do so; others do not know how.

## SCIENCE COURSES FOR INTRODUCTORY STUDENTS

Introductory science courses should help students construct basic concepts, integrate them into a coherent conceptual framework, and develop the reasoning ability necessary to apply them in situations not explicitly memorized. Significant progress toward these goals is not usually made in a traditional course. In particular, scientific reasoning skills must be expressly cultivated.

Physics instructors present lectures that include detailed derivations, lucid explanations, and suitable demonstrations. However, they often proceed from where they are now and do not remember where they were (or think they were) as students. They frequently think of students as younger versions of themselves. This approach is not well matched to an introductory class since fewer than 5 percent of the students will major in physics. (The percentages in chemistry and biology are a little higher.)

Meaningful learning requires active mental engagement. The challenge, especially in large courses, is how to achieve the necessary degree of intellectual involvement. Much of our research has been directed toward responding to that challenge in ways that are effective not only at our own university but in other instructional settings as well. We are developing *Tutorials in Introductory Physics* to engage students actively in learning physics.

## SCIENCE COURSES FOR K–12 TEACHERS

Science departments have a major responsibility for the education of K–12 teachers, both prospective and practicing. Many science faculty assume that this is a role solely for education faculty. In fact, the only place that the subject matter preparation of teachers can occur is in science courses. The study of educational psychology and methodology cannot help teachers develop the depth of understanding of science content that they need in order to teach effectively. The national effort to improve K–12 science education will not succeed without the direct involvement of science faculty.

The courses offered by most science departments do not provide adequate preparation for K–12 teachers. Descriptive courses are useless for preparing elementary and middle school teachers to help students learn basic concepts and reasoning skills. High school teachers are not adequately prepared by mainstream courses, including the sequence for majors. For example, the traditional introductory physics course and (to an even greater extent) upper division physics courses emphasize mathematical formalism. The breadth of topics covered allows little time for acquiring a sound grasp of the underlying concepts.

In addition to deficiencies in subject matter preparation, traditional science courses have another major shortcoming. Teachers tend to teach as they were taught. If taught through lectures, they are likely to teach that way. Moreover, this type of instruction is unlikely to lead to an understanding of the nature of science and thus does not help prepare teachers to teach science as a process of inquiry.

Teachers need to learn (or relearn) science in a way that is consistent with how they are expected to teach. For more than 25 years, our group has provided that opportunity through special physics courses for prospective and practicing K–12 teachers. These classes have provided an environment for research on the preparation needed for teaching physics and physical science by inquiry. The results have guided the development of *Physics by Inquiry*.

## RESEARCH AS A GUIDE FOR CURRICULUM DEVELOPMENT: AN EXAMPLE

Research guides the development of all curricula. The topics in *Tutorials in*

*Introductory Physics* respond to the questions: Is the standard presentation in textbook and lecture adequate to develop a functional understanding? If not, what can be done? The illustrative example below is discussed more fully in two published articles (Wosilait et al., 1998; Heron and McDermott, 1998.)

In teaching geometrical optics, most instructors begin with the premise that university students have a functional understanding of the rectilinear propagation of light. Virtually all students can state that "light travels in straight lines" and many can elaborate that "light travels outward from every point on an object in straight lines." To determine whether students can apply these concepts in a simple situation, we designed a written question.

### Pretest

Students were asked to predict the image formed on a screen by various light sources located in front of a small aperture in a mask. This question has been given as a pretest to thousands of introductory physics students and to more than 100 teaching assistants in our physics Ph.D. program. The question is called a "pretest" because it usually precedes the tutorial that we developed to address the difficulties that the responses of students revealed. (The question is actually a post-test in that students have already had the relevant material in their university course or K–12 education.)

One part of the question involves a long-filament bulb, a mask with a small triangular hole (~ 1 cm), and a screen. (See Figure B-1.) For a correct response, students must recognize that light travels in straight lines and that a line source can be treated as a series of point sources. The image can be found by treating each point on the bulb as a point source that produces a triangular image on the screen. Since the points are closely spaced, the images overlap substantially. The result is a vertical rectangle terminating at the top in a triangle.

Although the amount of prior instruction varied, the results did not. (See Table B-1.) Only about 20 percent of the students answered correctly, either before or after instruction. About 70 precent predicted that the image would be triangular. In this and many other instances, we have found that certain conceptual difficulties are not overcome by traditional instruction. Persistent difficulties must be explicitly addressed.

### Tutorial

The emphasis in the tutorials is on constructing concepts, developing reasoning ability, and relating physics formalism to the real world, not on solving standard quantitative problems. The tutorials are intended for use in a

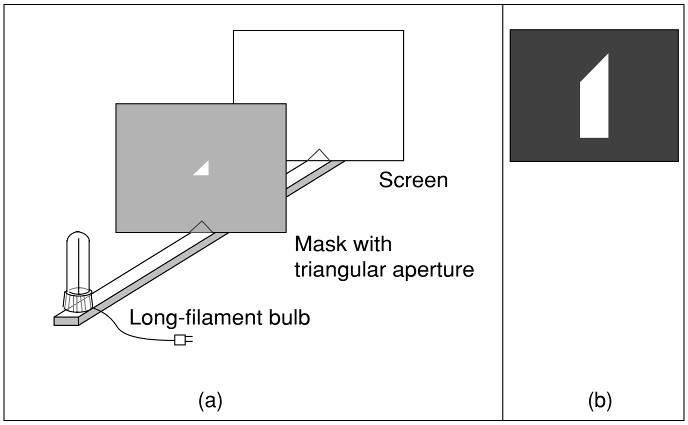

FIGURE B-1 Pretest.
(a) Students were asked to sketch what they would see on the screen.
(b) Correct answer.
SOURCE: Wosilait et al. (1998) and Heron and McDermott (1998). Reprinted with permission of the American Association of Physics Teachers and Optical Society of America.

small section of about 24 students, in which groups of three or four work together. The structure in these 50-minute sessions is provided by worksheets that guide students through a series of exercises and simple experiments by asking questions.

With results from questions like the one described above as a guide, we designed a tutorial entitled *Light and Shadow.* The tutorial begins by having students predict the images formed by point and line sources with apertures of various sizes and shapes. After making predictions and explaining their reasoning to one another, the students observe what actually happens and try to resolve any discrepancies with their predictions. They are then asked to predict and explain up-down and left-right inversions of images formed by asymmetric sources. These and other exercises help students recognize how the shape and relative size of the source and aperture and the distances involved affect the image.

Systematic monitoring in the classroom helped us improve the tutorial. One exercise that was added had a pronounced effect on student understanding of the geometric model for light. The students are asked to predict what they would see on the screen when a frosted light bulb is placed in front of a mask with a triangular hole. Many are surprised to see the inverted image of the bulb. Eventually, they realize that the entire bulb can be

TABLE B-1 Results from Pretest and Posttest Questions Administered in Introductory Physics Courses and Graduate Teaching Seminars

| | Introductory course Pretests (before tutorial) (N ≈ 1215) | Posttests (after tutorial) (N ≈ 360) | Graduate seminar Pretests (before tutorial) (N ≈ 110) |
|---|---|---|---|
| Correct or nearly correct | 20% | 80% | 65% |
| Incorrect: image mimics shape of hole in mask | 70% | 10% | 30% |

SOURCE: Wosilait et al. (1998) and Heron and McDermott (1998). Reprinted with permission of the American Association of Physics Teachers and Optical Society of America.

considered as a collection of point sources.

The students recognize that superposition of the images from the continuum of point sources produces an image that closely resembles the extended source, but is affected by the shape of the aperture. They also note that whether a light source can be treated as a point or extended source depends on a variety of factors.

### Posttest

Throughout the development of the tutorial, assessment played a critical role. In Figure B-2 is one of several posttest questions that we administered on examinations to about 360 students in several introductory courses. The percentage of correct or nearly correct responses was 80 percent, an increase from 20 percent on the pretest. Only 10 percent drew images the same shape as the aperture, in sharp contrast to the 70 percent who made this error on the pretest. (See Table B-1.)

The teaching assistants and postdocs who lead the tutorial sessions participate in a weekly graduate teaching seminar in which they work through the pretests and tutorials. About 65 percent have given a correct, or nearly correct, response for the question described above. This result is consistent with our experience that advanced study may not increase student understanding of basic topics.

We consider the pretest performance of graduate students to be a reasonable post-test goal for introductory students. As shown in Table B-1, the latter demonstrate a better functional understanding than the graduate students had initially had.

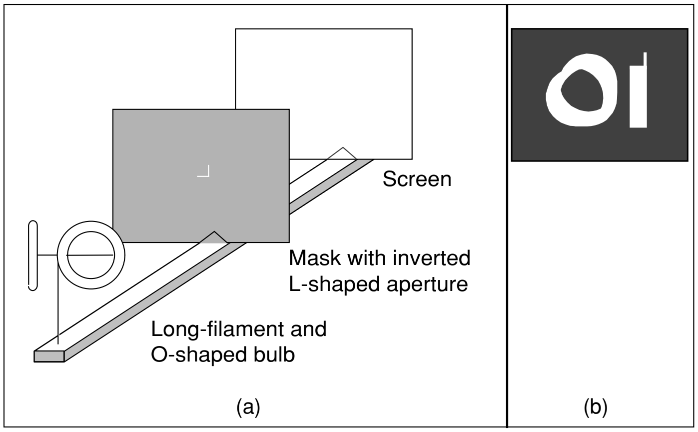

FIGURE B-2 Posttest question:
(a) Students were asked to sketch what they would see on the screen.
(b) Correct answer.
SOURCE: Wosilait et al. (1998) and Heron and McDermott (1998). Reprinted with permission of the American Association of Physics Teachers and Optical Society of America.

## COMMENTARY

It is tempting for instructors to think that the rectilinear propagation of light is such a simple concept that only a brief discussion of the topic is needed. Evidence to the contrary comes not only from our own research but from the experience of colleagues in our department. Recently, instructors of an honors section and a regular section of the calculus-based course used other approaches to teach this concept. Their students did not work through the tutorial.

In the honors section, the instructor demonstrated the image that is formed when light from an object passes through a pinhole. He asked questions to guide the students in explaining what they saw. He assigned homework based on equipment similar to that used in the tutorial. Only about 30 percent of the students responded correctly on the homework. The instructor then distributed solutions. In the regular section, the instructor did not lecture on the propagation of light through an aperture. However, he assigned homework problems that were similar to the instructional sequence in the tutorial. Prompt feedback was given in the form of written solutions.

Questions similar to the posttest question in Figure B-2 were posed on midterm examinations in both classes. Only 45 percent of the students in the honors section and 35 percent in the regular section gave correct, or nearly correct, responses. Although the time they spent on this material in lecture and on homework was not monitored, we do not believe that this factor alone could account for the large difference in posttest performance between these students and those who had worked through the tutorial. (See Table B-1.)

It has been our experience that if instruction does not engage students in confronting and resolving their underlying conceptual and reasoning difficulties, they do not develop the ability to do the reasoning necessary to apply concepts to problems that cannot be solved by memorized formulas. We attribute the success of students who worked through the tutorial to the detailed knowledge of student difficulties that informed its development.

The tutorials are a means of engaging students intellectually within the constraints of large, rapidly paced courses. More can be achieved if students can go through similar material more slowly and thoroughly. Teachers who have worked through the development of a ray model for light in *Physics by Inquiry* can deal successfully with more complicated combinations of light sources and apertures.

Research in physics education has shown that the development of a qualitative understanding greatly improves student performance on conceptual problems. Moreover, we and others have found that time spent in this way does not detract from (and often improves) proficiency in solving standard problems. Therefore, increasing the emphasis on qualitative reasoning can help set a higher (yet realistic) standard for student learning.

## CONCLUSION

A major goal of a science course that is likely to be terminal in the discipline is to help students recognize whether or not they understand the basic concepts. In *Physics by Inquiry*, and to a lesser extent in *Tutorials in Introductory Physics*, we try to help students learn to answer and to ask the kinds of questions that are necessary to assess and improve their understanding. This ability is critical for all students, but especially for those who plan to teach. Learning to reflect on one's own thinking transcends the learning of physics or any other science.

Our group has demonstrated that, in the context of physics, discipline-based education research can help improve student learning. Recently, there has been a steady increase in the number of physicists who are pursuing this type of research. The results are reported at professional meetings and in articles in refereed journals that are readily accessible to physics faculty (McDermott and Redish, 1999). Thus, colleagues who are not involved in education research have a rich resource from which to draw in developing print and computer-based instructional materials. Our experience indicates that it is difficult to develop effective curriculum that yields consistent positive results. Therefore, unless faculty can devote a long-term effort to the development and refinement of their own instructional materials, they should take advantage of already existing curriculum that has been carefully designed and thoroughly assessed.

Without a research base on student learning, we lack the knowledge necessary to make cumulative progress in improving instruction. There is a need in all the sciences for research on the intellectual development of students as they progress through a given body of material. Investigations of this type demand a depth of understanding that ordinarily is found only among specialists in a field. Therefore, such research must be conducted by science faculty in the context of courses offered by science departments.

The American Physical Society has issued a statement in support of research in physics education as a scholarly activity by faculty in physics departments. By taking similar action, other scientific societies could help strengthen efforts to improve student learning in their disciplines.

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## ACKNOWLEDGMENTS

Special thanks are due to the current faculty in the Physics Education Group: Paula R.L. Heron, Peter S. Shaffer, and Stamatis Vokos. In addition to past and present members of our group, I want to express my appreciation to the past and present leadership of the Physics Department and the University of Washington. I would like to recognize the early intellectual influence of Arnold B. Arons and the contributions by our physics colleagues here and elsewhere. I am also grateful to the National Science Foundation for enabling our group to do the research for which this CSSP Award is being given.

# Appendix
# C

# Workshop Agenda

**Criteria and Benchmarks for Increased Learning**
**from Undergraduate STEM Instruction**
**Committee on Undergraduate Science Education**
**National Research Council**
**500 Fifth Street, NW, NA Room 100**
**November 19–20, 2002**

## AGENDA

*Tuesday, November 19*

| | |
|---|---|
| 8:00 a.m. | **Continental breakfast** |
| 8:30 | **Welcome and introductions**<br>Bruce Alberts (President, The National Academy of Sciences)<br>Richard A. McCray (Chair, CUSE)<br>Robert L. DeHaan (Director, CUSE) |

8:45 **Discipline-based research in undergraduate STEM (USTEM) student learning: two pedagogical approaches to education research and practice at the introductory classroom level**

***Exemplar 1: Physics***

Paula R. L. Heron, University of Washington: Research as a guide to improving student learning in undergraduate physics.

9:30 ***Exemplar 1: Biology***

Brian Reiser, Northwestern University, BGuILE: Scaffolding student scientific inquiry in biology.

10:15 **Break**

10:30 **USTEM student learning: concurrent discipline-based working groups**

***Physics*** *(Facilitators: Laws, Henry)*

***Life sciences:*** *(Facilitators: Allen, Sundberg)*

***Geosciences:*** *(Facilitators: Olin, McCray)*

***Chemistry:*** *(Facilitators: Khan, Gosser)*

Each working group will complete three tasks: (1) Develop a list of a few additional examples of highly reputed courses/programs within its discipline; (2) come to agreement on the characteristics of each entry that justified its selection for the list (pedagogy, conceptual content, use of interactive IT, inclusiveness of diversity, social relevance, etc., being as specific in each category as possible); and (3) extract from those characteristics a list of criteria or indicators that would enable an observer to assess programs in that discipline. This list represents our "working hypothesis" regarding benchmarks and criteria for evaluating courses and programs.

11:30 **Working groups report: discussion**

12:15 p.m. **Lunch**

1:15 **Processes for development of student learning outcomes**

Barbara Baumstark, Georgia State University, Dept. of Biology

2:00 **Evaluating student outcomes: E=MC$^2$**
Gloria Rogers, Rose-Hulman Institute of Technology

2:45 **Break**

3:00 **Student outcomes: concurrent discipline-based working groups**
***Physics*** *(Facilitators: Wilson, Heron)*
***Life sciences***: *(Facilitators: Chamany, Uno)*
***Geosciences***: *(Facilitators: Brunkhorst, Lopez)*
***Chemistry***: *(Facilitators: Serum, Tong)*
Each working group has two tasks: (1) Prepare a consensus list of student outcomes for the discipline; and (2) identify conceptual and cognitive outcomes that might serve as cross-disciplinary learning goals.

4:00 **Working groups report: discussion**
*Both discipline-based and cross-disciplinary learning goals will be identified.*

4:45 **Tools for Assessing Quality USTEM Instruction: Reformed Teaching Observation Protocol (RTOP)**
Anton Lawson, Arizona State University, Dept. of Biology

5:30 **Day 1 plenary session adjourns**

*Wednesday, November 20*

8:00 a.m. **Continental breakfast**

8:30 **Curricular and pedagogical improvement: effecting faculty change**
Susan Millar, University of Wisconsin-Madison, WCER

9:15 **Barriers to change: resistance is the normative mode**
Elaine Seymour, University of Colorado, CARTSS

10:00 **Break**

10:15 **On encouraging faculty to pursue instructional reform**
Robert M. Zemsky, University of Pennsylvania, Graduate School of Education

11:00 **Institutional/departmental governance and incentives to promote quality USTEM instruction: a panel discussion**
Jack Wilson, UMassOnline
David F. Brakke, James Madison University
Herb Levitan, NSF, Education and Human Resources

12:30 p.m. **Lunch**

1:30 **General discussion: What did we learn? Next steps?**
Richard A. McCray, Robert L. DeHaan
*The discussion will focus primarily on the three overarching workshop questions: How to define and teach desired student outcomes? How to evaluate exemplary instruction? How to promote exemplary teaching at the institutional/departmental level?*

3:00 **Meeting adjourns**

# Appendix
# D

# Workshop Participants

Alberts, Bruce
National Academies
NAS President and NRC Chair

Allen, Deborah
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Department of Biological Sciences

Baumstark, Barbara
Georgia State University
Department of Biology

Boylan, Myles
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Division of Undergraduate Education

Brakke, David F.
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College of Science and Mathematics

Brenner, Kerry
National Academies
Board on Life Sciences

Brunkhorst, Bonnie J.
California State University, San Bernardino
Institute for Science Education

Chamany, Katayoun
Eugene Lang College, New School University
Science, Technology, and Society Program

DeHaan, Robert L.
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Center for Education

Drawbridge, Julie
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Department of Biology

Elgin, Sarah C.R.
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Office of the Provost

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Beloit College
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Kay, Alan C.
Viewpoints Research Institute, Inc.

Khan, Ishrat M.
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Lacampagne, Carol
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Center for Education

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Lawson, Anton
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Department of Biology

Layman, John
University of Maryland
Physics Education

Levitan, Herb
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Division of Undergraduate Education

Lopez, Ramon E.
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Department of Physics

McCray, Richard A.
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Department of Astrophysical and Planetary Sciences

McDermott, Lillian C.
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Physics Education Group

Millar, Susan B.
University of Wisconsin
Wisconsin Center for Education Research

Morse, M. Patricia
University of Washington
Department of Biology

Narum, Jeanne L.
Independent Colleges Office and Project Kaleidoscope

Olin, Robert F.
University of Alabama
College of Arts and Sciences

Ram, Preetha
Emory University
Department of Chemistry

Reiser, Brian J.
Northwestern University
School of Education and Social Policy

Rogers, Gloria M.
Rose-Hulman Institute of Technology
Institutional Research, Planning and Assessment

Schneps, Matthew
Harvard University
Science Education Department

Serum, James W.
SciTek Ventures

Seymour, Elaine
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Center to Advance Research and Teaching in the Social Sciences

Sharples, Fran
National Academies
Board on Life Sciences

Shuler, Sally Goetz
National Science Resources Center

Singer, Susan R.
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Department of Biology

Sundberg, Marshall
Emporia State University
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Tong, Lillian
University of Wisconsin
Center for Biology Education

Uno, Gordon
University of Oklahoma
Department of Botany and Microbiology

Weinburgh, Molly
Texas Christian University
Institute of Math, Science and Technology Education

Wesemann, Jode
American Chemical Society

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Department of Physics

Williams, Calvin
National Science Foundation
Division of Undergraduate Education

Wilson, Jack
UMassOnline

Woodin, Terry S.
National Science Foundation
Division of Graduate Education

Yuan, Robert
National Academies
Board of Life Sciences

Zeilik, Michael
University of New Mexico
Department of Physics and Astronomy

Zemsky, Robert M.
University of Pennsylvania
Graduate School of Education

# Appendix E

# Biographical Sketches of Workshop Attendees

## WORKSHOP STEERING COMMITTEE

**RICHARD A. McCRAY** (*Chair*) received a B.S. in physics from Stanford University in 1959 and a Ph.D. in theoretical physics from the University of California, Los Angeles, in 1967. He was a high school physics teacher from 1960–1962. McCray was a postdoctoral fellow at the California Institute of Technology (1967–1968) and an assistant professor at the Harvard College Observatory (1968–1971). In 1971, he moved to the Joint Institute for Laboratory Astrophysics at the University of Colorado at Boulder, where he is now George Gamow Distinguished Professor of Astrophysical and Planetary Sciences. He has held visiting positions at the NASA Goddard Space Flight Center (1983), Beijing University and Nanjing University (1987), the Space Telescope Science Institute (1988), Columbia University (1990), and the University of California at Berkeley (1997). In 1983 McCray was awarded a Guggenheim Foundation Fellowship, and in 1990 he received the Dannie S. Heinemann Prize for Astrophysics of the American Physical Society. He was elected to the National Academy of Sciences (NAS) in 1989. In 1996 he was appointed Concurrent Professor of Astronomy at Nanjing University and in 2002 he was awarded the National Science Foundation (NSF) Director's Award for Distinguished Teaching Scholar.

**BONNIE J. BRUNKHORST** is past chair of the National Council of Scientific Society Presidents and past president of the National Science Teachers Association (NSTA). Brunkhorst is a professor at California State University, San Bernardino, with a joint appointment in the College of Natural Sciences in geological sciences and in the College of Education in science, mathematics, and technology education. She is associate director of the University Institute for Science Education. She also taught secondary science for 15 years and supervised the K–8 science program in the Lexington, Massachusetts, public schools before receiving her Ph.D. She received her bachelor's and master's degrees in geology from Boston University, and her Ph.D. from the University of Iowa in science education with geology. She served as a member of the National Research Council's (NRC) National Committee on Science Education Standards and Assessment and on the Standards Executive Editorial Committee for the NAS. She also served as the coordinator and was cofounder for the national Salish Consortium for the Improvement of Science Teacher Preparation Through Research. Brunkhorst was awarded the 2002 NSTA Distinguished Service Award and received the NAS honorary appointment as national associate, first class.

**SARAH C.R. ELGIN** is professor of biology in the Department of Biology, Washington University, and holds joint appointments in the Department of Biochemistry and Molecular Biophysics, and the Department of Education. She received her B.A. in chemistry in 1967 at Pomona College and her Ph.D. in 1971 in biochemistry with James Bonner at the California Institute of Technology, where she also did postdoctoral studies with Lee Hood from 1971–1973. Her many honors and fellowships include Distinguished Faculty Award, Washington University, 1993; Overseas Fellow, Churchill College, Cambridge University, 1995–1996; Fellows Award, Academy of Science of St. Louis, 2000; and Howard Hughes Medical Institute (HHMI) Professor, 2002. Elgin directs Washington University's HHMI Undergraduate Biological Sciences Education Program, supporting undergraduate research opportunities and the development of investigative activities in the undergraduate curriculum. She works in precollege education through a curriculum development project, initially funded by a grant from the National Institutes of Health Science Education Partnership Award program (NIH/SEPA), which has produced a high school unit, Modern Genetics for All Students. She also participates in a course for K–8 teachers, Edu 6002 "Life Cycles and Heredity." Her goal is "not necessarily to produce a generation of scientists, but to produce citizens who are comfortable with science."

**RONALD J. HENRY** has been provost and vice president for academic affairs at Georgia State University since July 1994. One of his responsibilities is to develop Georgia State into a premier urban research university. Another responsibility is leadership to promote and recommend changes in public education systems that will improve success of Georgia students at all levels, preschool through postsecondary (P–16) and into the world of work. Previously, he served as chief academic officer for Miami University (Ohio) and Auburn University. Henry serves as chair of the Metro Atlantic P–16 Council. He is the principal investigator of a project cosponsored by the National Association of System Heads and the Education Trust to develop learning outcomes and standards for undergraduate education in several disciplines, including the natural sciences. In addition, he is the principal investigator on a Standards-based Teacher Education Project. Henry has just completed one term on NRC's Committee on Undergraduate Science Education (CUSE) and has been reappointed for a second term. He received his B.Sc. and Ph.D. degrees in applied mathematics from Queen's University, Belfast, in 1961 and 1964, respectively. He has been a fellow of the American Physical Society since 1974.

**JOHN R. JUNGCK** is Mead Chair of the Sciences and professor of biology at Beloit College. He is a fellow of the American Association for the Advancement of Science (AAAS). Jungck is principal investigator and cofounder of the BioQUEST Curriculum Consortium. Over the past sixteen years, he and his colleagues at other institutions have been leading the effort to build *The BioQUEST Library*, a collection of computer-based tools, simulations, databases, and textual materials that support collaborative, open-ended investigations in biology. Developed at campuses around the country, each module in the library simulates or models a different biological system, allowing students to analyze massive amounts of data and visualize the relationships among variables. Each module must involve students actively in learning, go through an intensive peer review process, and be proven effective in the classroom. Jungck is chair of the Education Committee of the Society for Mathematical Biology, the developer of numerous software packages in biology, coeditor of *Microbes Count!: Problem Posing, Problem Solving, and Persuading Peers in Microbiology*, and principal investigator of an NSF national dissemination project, "BEDROCK: Bioinformatics Education Dissemination: Reaching Out, Connecting, and Knitting-together."

**ALAN C. KAY** is currently president of Viewpoints Research Institute, Inc. He is best known for the idea of personal computing, the concept of the intimate laptop computer, and the inventions of the now ubiquitous overlapping-window interface and modern object-oriented programming. He is one of the inventors of the Smalltalk programming language and the architect of the modern windowing graphic user interface (GUI). He is especially interested in education and hopes that this new technology will help children to grow up thinking qualitatively better than most adults do today. Kay earned a B.S. in mathematics and molecular biology, University of Colorado, 1966; his M.S. in electrical engineering, University of Utah; and a Ph.D. in computer science, University of Utah, 1969. While at Utah he also contributed to the design of the ARPAnet (now known as the Internet). He became a researcher in the Stanford Artificial Intelligence Laboratory in 1969, and was one of the founders of the Xerox Palo Alto Research Center in 1970. After Xerox he was chief scientist at Atari, and from 1984 to 1996 was a fellow at Apple Computer, during which time he also taught children to use computers at the Open School in West Hollywood, California. In 1996, he joined Walt Disney Imagineering as a Disney Fellow and vice president for research and development.

**ISHRAT M. KHAN** is a professor of chemistry at Clark Atlanta University. He is connected with the NSF-sponsored Peer-Led Team Learning (Workshop Chemistry) projects. At Clark Atlanta, the chemistry department adopted and adapted Workshop Chemistry with substantial success. Khan has been recognized for his promise as a college-level science educator by being selected as one of Project Kaleidoscope's (PKAL) Faculty for the 21st Century. In this capacity he also served as assistant dean of the 2001 PKAL Summer Institute on Improving Undergraduate Science Education. He has co-organized three symposia at American Chemical Society (ACS) national meetings, including a 1999 international symposium on "Innovations in Polymer Science Teaching." In the summer of 2002, he coconvened a seminar entitled "New Chemistry" through the Faculty Resource Network at New York University. The seminar's goal was to encourage the introduction of frontier research areas into the undergraduate curriculum. Khan's research interests and publications are in the fields of synthetic biomacromolecules and biofunctional macromolecules with application in the general area of biomaterials (e.g., tissue engineering, drug-delivery). He has edited two ACS Symposium Series books and has over 50 refereed publications. Khan received his B.A. in chemistry in 1979 from Susquehanna University, and a Ph.D. in organic chemistry from the University of Florida in 1984.

**RAMON E. LOPEZ** is the C. Sharp Cook Distinguished Professor in the Department of Physics, University of Texas, El Paso. He received his B.S. in physics in 1980 from the University of Illinois, and his M.S. and Ph.D. in space physics in 1982 and 1986, respectively, from Rice University. He is a fellow of the American Physical Society (APS), and the recipient of the 2002 APS Nicholson Medal for Humanitarian Service to Science. Lopez is active in science education reform at a variety of levels. He has served as an education consultant for a number of school districts and state agencies around the country.

**LILLIAN C. McDERMOTT** is a professor of physics and director of the Physics Education Group at the University of Washington. She received her B.A. from Vassar College and a Ph.D. in experimental nuclear physics from Columbia University in 1959. She is a fellow of the AAAS and the APS. Among her most significant awards are the 2001 Oersted Medal of the American Association of Physics Teachers (the highest award of the AAPT), the 2000 Education Research Award of the Council of Scientific Society Presidents, and the 1990 Millikan Lecture Award of the AAPT. For more than two decades, McDermott has worked to establish research on the learning and teaching of physics as a field for scholarly inquiry by physicists. Under her leadership, the Physics Education Group conducts a coordinated program of research, curriculum development, and instruction. The group is deeply involved in the teaching of undergraduate physics and in the preparation of K–12 teachers. Graduate students in the group may earn the Ph.D. in physics by doing research in physics education. In addition, the group is actively engaged in faculty development through teaching assistant preparation seminars and professional development workshops for college and university faculty.

**ROBERT F. OLIN** is dean of the University of Alabama's (UA) College of Arts and Sciences. He joined the college in 2000 after serving 25 years on the faculty of the Virginia Polytechnic Institute and State University. He is the recipient of the 2002 Virginia B. Smith Innovative Leadership Award given by the Council for Adult and Experiential Leaning and the National Center for Public Policy and Higher Education. Under his leadership, UA's College of Arts and Sciences opened the Mathematics Technology Learning Center, a 240-computer math learning community located in UA's largest residence hall. In

2001, the center received a Special Award of Merit from the Alabama Quality Council. A strong proponent of the value of learning communities, Olin has also led in the development of undergraduate residential learning communities at UA, including the Parker-Adams Freshmen Year Program. The center is based on an innovative program developed by Olin when he served as chairman of Virginia Tech's Department of Mathematics. The department of mathematics at Virginia Tech was named Exemplary Department in Virginia Tech's College of Arts and Sciences and a University Exemplary Department. The department established two endowed faculty chairs, expanded its graduate program, and increased access to mathematics courses for Virginia's secondary teachers through online instruction. Olin received a bachelor's degree in mathematics in 1970 from Ottawa University in Kansas and a doctorate in mathematics in 1975 from Indiana University, Bloomington.

**JAMES W. SERUM** is the founder and president of SciTek Ventures, a consulting company that helps young companies deal with the challenges of bringing science, technology, and business planning together in a focused, cohesive manner. Serum is also a venture partner at Flagship Ventures. He is on the boards of directors of Nanostream, Genstruct, and engeneOS. He was the cofounder, director, executive vice president, and chief operating officer for Viaken Systems, Inc. Previously he worked at the Hewlett Packard Company for 26 years where he held a variety of positions in research and development, marketing, and general management. Serum was the founder of Hewlett Packard's Bioscience Products business and served as chairman of the company's Pharmaceutical Business Bioscience Council and cochairman of the Corporate R&D Council. He received a B.A. in chemistry from Hope College and was awarded a Ph.D. in organic chemistry in 1969 from the University of Colorado. His doctorate research was directed toward studies in mass spectrometry. Following his graduate studies, he taught and did research at the University of Ghent, Belgium.

**SUSAN R. SINGER** is currently professor of biology at Carleton College, with which she has been associated since 1986. She received her B.S. summa cum laude in 1981, her M.S. in 1982, and her Ph.D. in 1985, all from Rensselaer Polytechnic Institute (RPI). She was chair of Carleton's Department of Biology from 1995–1998 and served as program officer for developmental mechanisms at the NSF from 1999 to

2000. She also chaired the Education Committee of the American Society of Plant Biologists and has been involved in numerous other educational efforts at the national level. Her teaching interests include Carleton's Triad Program, which is an integrated first-term experience that brings a group of students together to explore a thematic question across disciplinary boundaries by enrolling in three thematically linked courses. Singer also directs the Perlman Center for Learning and Teaching at Carleton. The Perlman Center sponsors conversations, encourages reflection, and offers a venue for classroom innovations that bear on the challenges and opportunities of education at a distinctive liberal arts college. The goal of the center is to join student insights with faculty perspectives in an ongoing discussion about both the reliable and the elusive elements that foster and constrain learning.

**CARL E. WIEMAN** is Distinguished Professor of Physics at the University of Colorado and winner of the 2001 Nobel Prize in physics for studies of the Bose-Einstein Condensate. He has been a member of the NAS since 1995. Since 2000, Wieman has worked on the National Task Force for Undergraduate Physics, which emphasizes improving undergraduate physics programs as a whole: introductory and advanced courses for all students, preparation of K–12 teachers, undergraduate research opportunities, and the recruitment and mentoring of students for diverse careers. He is a 2001 recipient of an NSF Director's Award for Distinguished Teaching Scholars. Wieman received his Ph.D. from Stanford University in 1977.

## NATIONAL ACADEMIES STAFF

**Bruce Alberts** is president of the NAS and chair of the NRC, the principal operating arm of the National Academy of Sciences and the National Academy of Engineering. He is a respected biochemist recognized for his work in both biochemistry and molecular biology and is known particularly for his extensive molecular analyses of the protein complexes that allow chromosomes to be replicated. Alberts joined the faculty of Princeton University in 1966 and after 10 years moved to the medical school of the University of California, San Francisco (UCSF). In 1980, he was awarded an American Cancer Society lifetime research professorship. In 1985, he was named chair of the UCSF department of biochemistry and biophysics. Alberts is one of the principal authors of *The Molecular Biology of the Cell*, now in its third edition, considered the leading advanced textbook in this field and used widely in U.S. colleges and universities. His most recent text, *Essential Cell Biology*, is intended to present this subject matter to a wider audience. He is committed to the improvement of science education; he helped to create City Science, a program for improving science teaching in San Francisco elementary schools.

**Robert L. DeHaan** is the director of CUSE in the NRC's Center for Education. DeHaan came to CUSE in January, 2002, from Emory University, where he was the Charles H. Candler Professor of Cell Biology, Emory Medical School, and adjunct professor in the Division of Educational Studies. DeHaan received his Ph.D. from the University of California, Los Angeles, in 1956. In 1995, DeHaan created a precollege science education outreach effort called the Elementary Science Education Partners (ESEP) program. DeHaan's work in the schools with ESEP has been cited by the National Academy of Sciences Resources for Involving Scientists in Education (RISE) program as an exemplary professional development project and by the National Science Resources Center as a Center of Excellence. In addition, in 1998 he received the First Bruce Alberts Award from the American Society of Cell Biologists for Distinguished Contributions to Science Education. He received the Thomas Jefferson Award from Emory as a "Lifetime Leader in Scholarship and Teaching." He holds an appointment as lifetime fellow of the American Association for the Advancement of Science and is winner of the 1993 Gregor Mendel Medal from the University of Brno, Czech Republic, for his research in cell biology and development. DeHaan founded and was the first director of the Emory Center for Ethics in Public Policy and the Professions and remains a faculty scholar at the Center.

## WORSKHOP PRESENTERS

**Barbara Baumstark** received her Ph.D. in biochemistry from the Massachusetts Institute of Technology. Since 1984, she has been a faculty member at Georgia State University (GSU), where she is currently professor in the Department of Biology. Baumstark served as graduate director for the Biology Department for 12 years before becoming its director of instructional programs in 2001. Her educational services include participation in the Quality in Undergraduate Education (QUE) Standards Project, the Standards-based Teacher Education Project (STEP) Science Committee, the Performance Assessment of Colleges and Technical Schools (PACTS) Science Subcommittee, and the Advisory Board of BioTrek, a division of SciTrek of Atlanta. In 1999, Baumstark initiated the Bio-Bus Project, an outreach program that uses a 30-foot mobile instructional laboratory to bring exciting science activities to Georgia's schoolchildren. She has also been the principal investigator for a Graduate Assistance in Areas of National Need (GAANN) award through the U.S. Department of Education and currently directs a state-funded project designed for the recruitment and retention of minorities in the biological sciences. Baumstark has been the recipient of GSU's College of Arts and Sciences Outstanding Junior Faculty Award and, in 2001, received the university's Instructional Innovation Award.

**David F. Brakke** is a limnologist who has published extensively on a range of topics related to surface water chemistry and watershed biogeochemistry, as well as applied problems in ecosystem, watershed, and lake management. He has served as associate editor for the leading journal *Limnology and Oceanography* and currently writes a column on science and society for the *Association of Women in Science Magazine.* For several years Brakke has been involved in a number of major national projects and initiatives related to science, mathematics, and technology education, undergraduate research, teacher preparation, and ongoing professional and leadership development of K–12 teachers and college faculty. He is currently dean of science and mathematics at James Madison University, where he is continuing work to improve science and mathematics education for all students across the country.

**Paula R.L. Heron** is an assistant professor of physics at the University of Washington. She received a B.Sc. in physics from the University of Ottawa and a Ph.D. in theoretical condensed matter physics from the University of Western Ontario in 1995. She joined the Physics Education Group at the University of Washington in 1995. With Lillian C. McDermott, she was awarded the 2000 Archie Mahan Prize of the Optical Society of America for the best article in *Optics and Photonics News.* Heron is currently a member of the APS Forum on Education Executive Committee, the AAPT Committee for Women in Physics, and the AAPT Committee on Teacher Preparation. She consults on several NSF–funded education projects. Heron is engaged in an ongoing investigation of difficulties that students encounter in applying concepts from introductory physics in their subsequent studies. This research takes place in courses on thermal physics that are beyond the introductory level and in courses on mechanics that are taught from an engineering perspective. Findings from this research are guiding the development and modification of curriculum for introductory and advanced physics courses, including courses for precollege teachers.

**Anton Lawson** is currently in the Department of Biology at Arizona State University. He received his B.S. in biology from the University of Arizona in 1967, his M.S. in biology from the University of Oregon in 1969, and his Ph.D. in science education from the University of Oklahoma in 1973. Lawson's research centers on the nature and development of scientific thinking patterns, such as hypothetico-deductive, probabilistic, proportional, combinatorial, analogical, and correlational reasoning. Major interests involve determination of factors that influence the development of these thinking patterns during childhood and adolescence and determination of their relationship to each other and to scientific concept acquisition. The goal is to generate and test explanatory theories of the development of thinking patterns and develop neurological models of cognition. Classroom implications are sought with the intent of improving science instruction. Lawson received the Outstanding Science Educator of the Year (1981) award from the Association for the Education of Teachers in Science. He also received the award for Distinguished Contributions to Science Education Research (1986) from the National Association for Research in Science Teaching (NARST) and was honored with the *Journal of Research in Science Teaching* award for outstanding research paper in 1976, 1985, and 1987 by the NARST.

**Herb Levitan** is currently serving as section head for the Division of Undergraduate Education, Directorate for Education and Human Resources, at the NSF. His responsibilities include administrative association with the Course, Curriculum, and Laboratory Improvement (CCLI) program and the NSF Director's Award for Distinguished Teaching Scholars (DTS) and contributions to the review of life sciences and interdisciplinary proposals. Levitan has been a permanent NSF employee in the Division of Undergraduate Education since 1993. He came to the NSF as a visiting scientist in 1990 after serving as a faculty member in the Zoology Department at the University of Maryland, College Park, for more than 20 years. At the University of Maryland, he taught graduate and undergraduate courses in neurophysiology, electrophysiology, pharmacology, and cell biology and directed the department's honors program. He received his Ph.D. in electrical engineering from Cornell

University. His postdoctoral research in neurobiology was conducted at the Brain Research Institute of the University of California, Los Angeles; the Centre d'Etude de Physiologie Nerveuse in Paris; and the National Institute of Mental Health in Bethesda. He also served as senior staff associate at the National Institute of Child Health and Human Development.

**Susan B. Millar** is a senior scientist with the University of Wisconsin-Madison's Wisconsin Center for Education Research (WCER). A cultural anthropologist by training (Cornell, Ph.D., 1981), her work during the last fifteen years has focused on organizational change processes and student and faculty learning associated with efforts to improve education in the science and engineering disciplines. At this time, she pursues these topics as an evaluator for two major NSF-funded projects being launched at WCER in 2003—the Systemwide Change for All Learners and Educators and the Center for the Integration of Research on Teaching and Learning—and as the lead evaluator for the Regional Workshop Program, a nationwide science faculty development project. Millar is also the external evaluator for the Center for the Advancement of Engineering Education at the University of Washington. In addition, as codirector of the IceCube Education Resource Center, she is using knowledge gained as an evaluator to help build the education and outreach arm of a major astrophysics experiment. She was founder and director of Learning through Evaluation, Adaptation, and Dissemination (LEAD) Center (1994–2002).

**Brian J. Reiser** is professor of learning sciences in the School of Education and Social Policy at Northwestern University. He served as chair of the learning sciences Ph.D. program from 1993, shortly after its inception, until 2001. His research focuses on the design and enactment of supportive environments for student inquiry in science. The goal of this work is to develop a model of "reflective inquiry" and the pedagogical principles for its support. These projects investigate the design of interactive learning environments that scaffold scientific investigation, reflection, and argumentation; design principles for technology-infused curricula that engage students in inquiry projects; and the teaching practice that supports student inquiry. Reiser's work is part of the initiatives of the NSF Center for Learning Technologies in Urban Schools, which is working to understand how to make learning technologies a pervasive part of science classrooms in urban schools, and the newly funded NSF Center for Curriculum

Materials in Science. He received his doctorate in cognitive science from Yale University in 1983.

**Gloria M. Rogers** is currently the vice president for institutional research, planning, and assessment at Rose-Hulman Institute of Technology. In addition to her duties at Rose-Hulman, she has been active presenting seminars on the development and implementation of assessment plans to improve educational programs. Rogers currently serves as a consultant to the Accreditation Board for Engineering and Technology on the implementation of the new outcomes-based accreditation criteria for engineering and engineering technology and serves as a consultant-evaluator for the Higher Learning Commission of the North Central Association regional accreditation. She is also a facilitator and presenter for the American Association of Higher Education and the Higher Learning Commission regional institutional workshops, “Changing Institutional Priorities.” In 1998–1999 she was a NSF/American Society of Engineering Education Visiting Scholar, working with engineering programs in the area of assessment. She has organized four national symposia on “Best Assessment Processes.” Rogers has been the cochair of the Rose-Hulman Commission on Assessment of Student Outcomes, which is responsible for the design, development, and implementation of the RosE-Portfolio, an electronic, web-based student portfolio system.

**Elaine Seymour** has served as the director of ethnography and evaluation research at the University of Colorado, Boulder, since 1989. In 2002, she and her group were invited to become part of the university’s new Center to Advance Research and Teaching in the Social Sciences (CARTSS). Important foci for her work have been the study of factors contributing to attrition from undergraduate science, mathematics, and engineering majors and evaluation of national and institution-based initiatives that seek to improve quality and access in undergraduate science. Evaluation work includes two NSF-funded national chemistry consortia. She is currently synthesizing findings from several science education initiatives involved in changing undergraduate science. Seymour has codeveloped online assessment and evaluation tools for faculty engaged in classroom innovation, most notably the Student Assessment of their Learning Gains (SALG) instrument (with S.M. Daffinrud, University of Wisconsin-Madison), and the Field-Tested Learning Assessment Guide (FLAG). Academic and professional honors include the 2000 Betty Vetter Award for Research on Women in

Engineering from Women in Engineering Programs and Advocates Network (WEPAN), teaching excellence awards, a Fulbright Teaching Scholarship, and doctoral fellowships from the National Institute of Mental Health and the University of Colorado. She received a B.A. Honors in economics and political science from Keele University, England; an M.A. in education from the University of Glasgow, Scotland; and both her M.A. and Ph.D. in sociology from the University of Colorado, Boulder.

**Jack Wilson** is the founding chief executive officer of UMassOnline. He came to UMassOnline from Rensselaer Polytechnic Institute (RPI), where he was the J. Erik Jonsson '22 Distinguished Professor of Physics, Engineering Science, Information Technology, and Management. While at Rensselaer, he became known for leading a comprehensive restructuring of the academic program that was recognized with the Theodore Hesburgh Award, the Pew Prize, and the Boeing Prize. During his eleven-year career at RPI, he served as dean of undergraduate education, dean of professional and continuing education, interim provost, interim dean of faculty, and as founding director of the Anderson Center for Innovation in Undergraduate Education. He is also known as an entrepreneur and a consultant to many computing and communications firms. He was the founder, first president, and only chairman of LearnLinc Corporation (now Mentergy), a supplier of software systems for corporate learning in Fortune 1000 Corporations. Wilson served as one of sixteen International Consulting Scholars for the IBM Corporation. Wilson is a fellow of the APS and was awarded the Distinguished Service Citation from the AAPT.

**Robert M. Zemsky** served through 2001 as the founding director of the University of Pennsylvania's Institute for Research on Higher Education, one of this country's major public policy centers for postsecondary education. Trained as an historian, Zemsky's early work focused on the nature of political processes in the eighteenth and nineteenth centuries. Since the 1970s his research has centered on how colleges and universities, in a world increasingly dominated by market forces, can be both mission-centered and market-smart. Within the University of Pennsylvania, Zemsky has served as the university's chief planning officer, and as master of Hill College House. In 1998, *Change* named him as one of higher education's top 40 leaders for his role as an agenda setter. He is a former Woodrow Wilson Fellow. He was a postdoctoral Social Science Research Council Fellow in Linguistics and was later chair of that council's Committee on Social Science Personnel. In 1998, he received a Doctor of Humane Letters (Hon.) from Towson University.

## WORKSHOP FACILITATORS

**Deborah Allen** is an associate professor and undergraduate programs director in the Department of Biological Sciences, University of Delaware. She earned a Ph.D. in biological sciences from the University of Delaware and pursued research interests in the area of water and electrolyte homeostasis. A more recent focus has been science education, including the development of a two-semester problems-based-learning (PBL) course in introductory biology. She has been involved in the development of a program for undergraduate PBL peer group facilitators and is currently working with other science educators to design a "science semester" for elementary teacher education majors that will incorporate multidisciplinary PBL problems. She is also working with a statewide committee of teachers and college faculty to design curriculum activities for 10th grade biology in Delaware's public schools and coteaches the summer professional development courses that support teachers' use of the activities. She is a founding leader of the Institute for Transforming Undergraduate Education and recipient of a 1999 TIAA-CREF Theodore M. Hesburgh Certificate of Excellence for faculty development programs.

**Katayoun Chamany** is on the faculty of the Science, Technology, and Society Program at Eugene Lang College, New School University, an undergraduate science literacy program focused on teaching science in the context of society. A director of this program, she developed an innovative curriculum and established internships and partnerships with other universities to broaden the student experience. Currently, she teaches courses in the program that cover infectious diseases, biotechnology, cell biology, science writing, and genetics. Chamany received the Distinguished University Teaching Award from New School University in 2000. She is dedicated to achieving scientific literacy for all undergraduates and the general public and has developed seminars, workshops, and educational materials that reflect an interactive and case-based method of teaching. Currently, Chamany is researching and developing educational tools to accompany traditional biology textbooks and courses. These tools will incorporate economic, social, and political perspectives with those of the natural sciences in a multimedia format. She received her Ph.D. in molecular and cell biology at the University of California, Berkeley, in 1996 and a B.A. in biology from the University of Iowa in 1989.

**David K. Gosser, Jr.** received a Ph.D. in physical inorganic chemistry at Brown University. He has published in the fields of theoretical and applied electrochemistry and bioelectrochemistry, including an electrochemical study of the antimalarial mechanism of the Chinese natural drug artemisinin and the monograph "Cyclic Voltammetry: Simulation and Analysis of Reaction Mechanisms." Gosser has led the development of peer-led team learning at the City College of New York since 1991 and has led national projects oriented around peer-led team learning (Workshop Chemistry, 1995–1999; Peer-Led Team Learning: National Dissemination, 1999–2003). His current areas of interest are in the connection between the peer leaders' experience and interest and success in career choices such as teaching or careers in scientific research.

**Priscilla Laws** currently holds the position of professor of physics at Dickinson College. She received her bachelor's degree from Reed College in 1961 and a Ph.D. from Bryn Mawr College in theoretical nuclear physics in 1966. Her research interests have included the health effects of medical and dental X-rays, the impact of energy use on the environment, and the uses of experiential approaches and computers to enhance learning in physics. Laws is coordinator of the Workshop Physics project in which interactive teaching methods, direct experience, and the use of computer tools replace traditional lectures. She has extensive experience leading teacher workshops in the United States and abroad and has received awards for software design and curriculum innovation in the sciences from EDUCOM/NCRIPTAL, *Computers in Physics*, the Sears-Roebuck Foundation, and the Merck Foundation. In 1993, she received the Dana Foundation Award for Pioneering Achievement in Education with Ronald K. Thornton; and in 1996, the AAPT bestowed on her the 1996 Robert A. Millikan Medal for notable and creative contributions to the teaching of physics. Laws and five of her colleagues are currently involved in an NSF Teacher Enhancement project to conduct summer institutes, both at Dickinson College and the University of Oregon, for high school teachers who want to conform to new national and local science education standards.

**Marshall Sundberg** is a plant anatomist/morphologist interested in ontogeny and the role of plant development in ecological and evolutionary adaptation.

He is also interested in improving science education and has published on curriculum design, assessment, and student-active learning. He received a B.A. from Carleton College (1971), and M.S. (1973) and Ph.D. (1978) degrees from the University of Minnesota and is currently on the faculty of the Department of Biological Sciences, Emporia State University. Sundberg is a recipient of the Charles E. Bessey Award for botanical education from the Botanical Society of America and the Four-Year College Biology Teaching Award from the National Association of Biology Teachers (NABT). Areas of his current research include the evolutionary origin of the maize ear, development of the separation zone in Tabasco pepper fruits, and designing interventions to help students overcome common biological misconceptions.

**Lillian Tong** currently holds the position of faculty associate, professional development programs, at the Center for Biology Education, University of Wisconsin-Madison. She received her Ph.D. at the University of Michigan and did thirteen years of postdoctoral research at UW–Madison in neuroscience of the visual system. She left laboratory research to help establish the Center for Neuroscience at UW-Madison and in 1992 joined the Center for Biology Education to facilitate improvement of undergraduate biology education. Her primary focus is to bring together faculty and staff from departments across campus to share ideas and work collaboratively on science teaching and learning issues. With their input, she identifies impediments to achieving their goals (from administrative to student learning barriers), develops programs, and provides resources to address the needs with a menu of opportunities. Tong has been active in the UW-Madison Teaching Academy, the College of Agricultural and Life Sciences Instructional Improvement Committee, and as a partner in Creating a Collaborative Learning Environment, a cross-disciplinary faculty/staff community.  Nationally, she has participated in the Coalition for Education in the Life Sciences, PKAL, and Faculty for Undergraduate Neuroscience.

**Gordon E. Uno** joined the Department of Botany and Microbiology at the University of Oklahoma in 1979, was appointed a David Ross Boyd Professor of Botany in 1997, and is currently serving as the department's chair. Uno was a program officer in the Division of Undergraduate Education at the NSF in 1998–2000 and serves on the editorial boards of four science and science education journals. He was awarded honorary membership by the NABT in 2001 and was its president in 1995. He became a AAAS fellow in 2000, and he has received one national, one state, and three university-level teaching awards. Uno has taught over 6,000 undergraduates and has led many faculty development workshops for university and secondary science instructors.